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COAL GASIFICATION STUDY HANDBOOK.(U)

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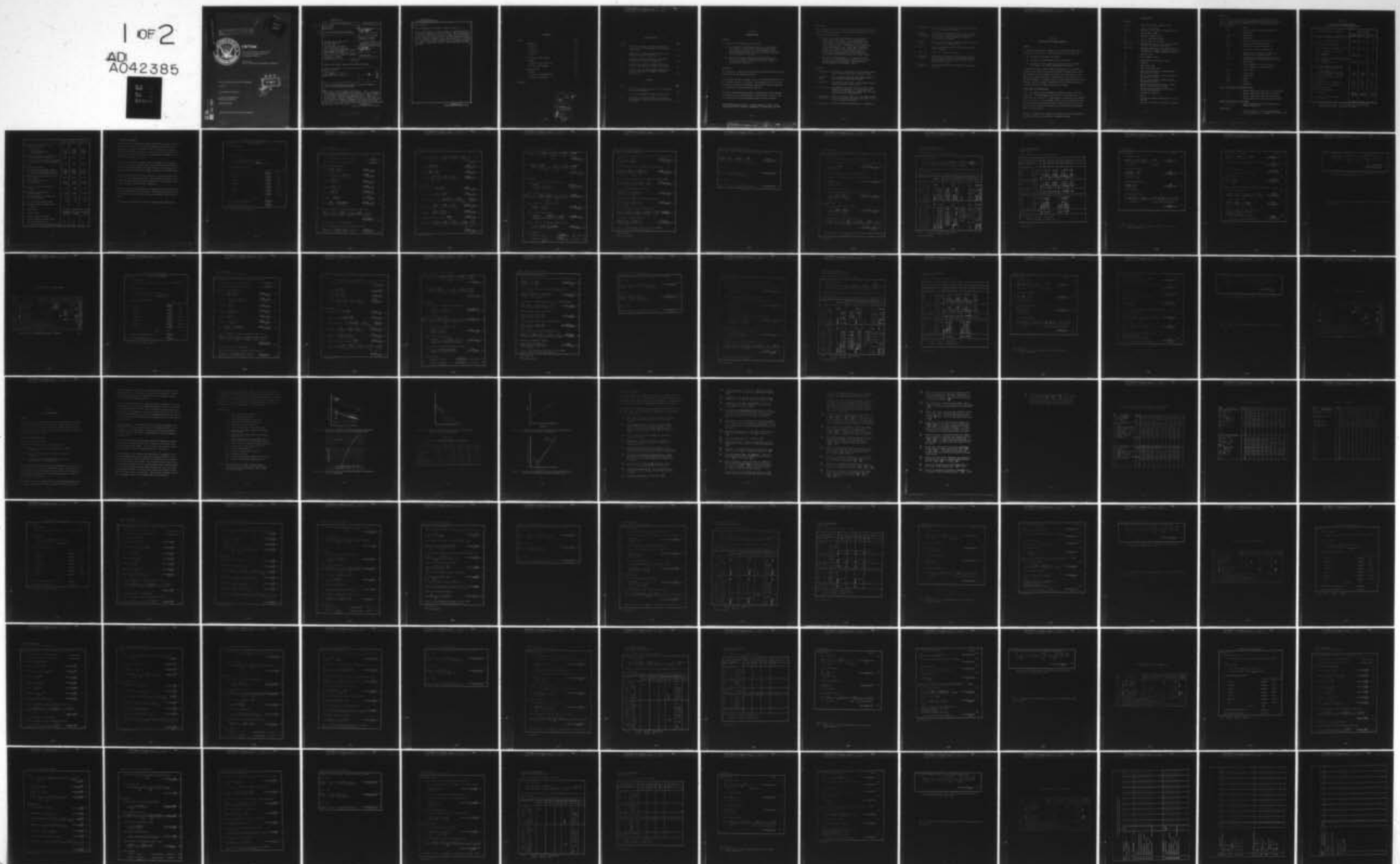

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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

COAL GASIFICATION STUDY HANDBOOK

April 1977

An Investigation Conducted by

BECHTEL CORPORATION
San Francisco, California

N68305-76-C-0009

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The purpose of this handbook is to provide: first, a procedure for evaluating the costs of a coal gasification plant in terms of the capital investment and operating costs. These are to be sensitive to several parameters defining coal, fuel gas, and sulfur emissions; second, a procedure for the derating of Navy base boilers, to reflect the change in performance resulting

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from introduction of fuel gas in place of coal or oil.

The gas plant analysis is based in part on a detailed analysis of the gas treatment section of the plant. The remaining part of the plant performance is based on conventional stoichiometry and near approach to equilibrium in the gas production section. The boiler derating method is based on observations of the relative contribution to heat transfer made by radiation and convection, and on conventional relations describing these transfer processes.

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Section 1

INTRODUCTION

PURPOSES

The function of this handbook is to provide:

- A procedure for evaluating the costs of a coal gasification plant in terms of the capital investment and operating costs. These are to be sensitive to several parameters defining coal, fuel gas, and sulfur emissions. Hand calculation is practical.

- A procedure for the derating of Navy base boilers, to reflect the change in performance resulting from introduction of fuel gas in place of coal or oil. Hand calculation is practical.

BACKGROUND

The techniques of computation are based on principles discussed in the final report on the subject contract.*

The gas plant analysis is based in part on a detailed analysis of the gas treatment section of the plant. The remaining part of the plant performance is based on conventional stoichiometry and near approach to equilibrium in the gas production section.

The boiler derating method is based on observations of the relative contribution to heat transfer made by radiation and convection, and on conventional relations describing these transfer processes.

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*Civil Engineering Laboratory. Contract Report CR 77.013, "Coal Gasification Study," Bechtel Corporation, San Francisco, CA, 1977.

PROFICIENCY

Both procedures below are to some extent the extrapolations of performances calculated in detail. Their accuracy is tied in part to the validity of the base system.

- The gas plant analysis is expected to be capable at nearly all heating values of coal (perhaps down to 6,000 Btu/lb). Fortunately, the thermodynamic character of the gasifier performance forces the calculated effects to apply. The method has not been tried on low heating value coals. There are, furthermore, limits to the range of performance which can be reasonably described by the gas treatment process. These are the ranges covered in the computer runs and presented in graphical form in the contract report.

- The boiler derating method is of a proficiency sufficient for conceptual design, falling off in accuracy as extrapolation is lengthened. Some comments on validity appear in the contract report.

GLOSSARY

1. Combustibles — Considered in this report to be the gaseous components of useful fuel value, exclusive of H_2S.

2. Fire Tube Boiler — A boiler in which the hot gases pass through the main exchanger tube bundle "in-tube."

3. Fuel Gas — Considered in this report to be the gases from the reactor exclusive of water vapor.

4. Hot Fuel Gas — Considered in this report to be all the hot raw gases from the reactor. Cool fuel gas is considered to be the same, but leaving the waste heat recovery section at perhaps $350^{o}F$.

5. High Heating Value, HHV — Considered in this report to be the higher heating value of the 100 lb coal used as the basis for the reactor performance analysis.

6. Product Gas — The gas exported from the plant for consumption.

7.	Quench Water	— The low pressure steam injected for quench purposes in the entrained solids reactor.
8.	Savings Investment Rates (SIR)	— The ratio of the present value of savings offered by the subject investment program divided by the present value of the investment required for instituting that program.
9.	Service Factor	— The percentage of time for which a plant, or section of a plant, is operating usefully.
10.	Sour Gas	— A gas containing hydrogen sulfide and other minor sulfur compounds.
11.	Sweet Gas	— A gas free of sulfur components.
12.	Waste Heat Recovery	— Generally, the recovery of sensible heat from hot gases, but more specifically in the present analysis considered as the recovery of heat from the raw hot reactor gases.
13.	Water Tube Boiler	— A boiler in which the main exchanger carries water "in-tube."

Section 2

GASIFICATION PLANT ANALYSIS

SUMMARY

The computation scheme for analysis of a coal gasification plant is presented in this section. The main features of the scheme are:

- Evaluation of gasifier performance
- Evaluation of gas treatment for sulfur removal
- Evaluation of the capital and operating costs, including unit product cost, using discounted future costs

The method applies to typical reactors operating in a fluidized or entrained solids mode with either air/steam or oxygen/steam as blast. The rationale for the analysis is given in the final report to the Navy for the present contract. The results of the analysis are considered to support a conceptual design. Within several sets of results developed from the analysis, comparisons can be drawn about the performance and costs of gasification and gas cleanup.

SYSTEM DATA AND NOMENCLATURE

Each of the nominal cases represents a different gasifier type and blast mode. The performance of each can be characterized by a set of values set out in Table 2-1. With these it is possible to fix approximately the rates of flow of oxygen, steam, and coal necessary to operate in a manner which extends the past experience with the reactors. Similar data are presented to support the calculations in subsequent parts of the procedure.

The list of nomenclature contains the symbols used in the computation procedure. Units are identified in computation steps.

NOMENCLATURE

Variables

C_p, C'_p	=	Molal heat capacity; Specific heat
C	=	Capital cost, dollars
$e(SO_2)$	=	Emission of SO_2, lb per 10^6 Btu HHV (Coal)
E	=	Energy, Btu or kWhr
ΔH	=	Enthalpy change, Btu/mol
ΔH_c	=	Heat of combustion, Btu/mol
ΔH_f	=	Heat of formation, Btu/mol
HHV(coal)	=	High heating value of coal, dry, Btu/100 lb of moist coal charged to gasifier
HHV'(coal)	=	High heating value of coal, dry, Btu/100 lb of moist coal charged to gasifier, for which the fraction of carbon converted becomes γ
n	=	Number of mols
Σn_i	=	Total number of mols
O	=	Operating cost, dollars per year
P	=	Pressure
Q	=	Heat effect, Btu
ΣQ	=	Total heat effect, Btu
R_{wc}	=	Ratio of total water to carbon charged to the gasifier, mol/mol
R_{qc}	=	Ratio of quench water to carbon charged to the gasifier, mol/mol
R_{oc}	=	Ratio of free oxygen to carbon charged to the gasifier, mol/mol
R_{bc}	=	Ratio of blast gas (not steam) to carbon charged to the gasifier, mol/mol
R_{ps}	=	Fraction of high pressure steam going to process (165 psia) use
T	=	Temperature, degrees F
W	=	Weight
α	=	Fraction of gasified carbon which is carbon monoxide
γ	=	Fraction of carbon in coal which is gasified

Subscripts

Certain quantities, usually mols of a species representing some portion of a large quantity or associated with some feature of the system will be identified by the subscripts below, if not by other commonly recognized symbols.

blst	=	Blast
CFG	=	Cool fuel gas, from reactor, moist, sour
c	=	Combustion
cmbsl	=	Combustible
evap	=	Evaporation
FG	=	Fuel gas, from reactor, dry basis, sour
HFG	=	Hot fuel gas from reactor, raw
H_2,CO	=	Hydrogen/carbon monoxide mixture
H_2O_d	=	Water that undergoes decomposition
$H_{2,fc}$	=	Hydrogen, net, in coal after some loss to combination with oxygen in coal
$H_{2,n,fg}$	=	Hydrogen net in fuel gas after some loss to combination with oxygen and sulfur in coal
hp	=	High pressure
i	=	i the component, or process features
j	=	j the component, or process feature
N_2,O_2	=	N_2/O_2 *mixture*
PG	=	Product gas
qnch	=	Quench water
rctr	=	Reactor
Stm	=	Steam
x	=	Expansion

Numeral Subscripts – Performance Study

0	=	Denotes association with feed coal to gasifier.
1	=	Denotes association with blast to gasifier
2	=	Denotes association with hot raw fuel gas
3	=	Denotes association with waste heat recovery

Numerical Subscripts – Cost Study

1,2,3, etc	=	Used to identify capital or operating cost items as indicated

Superscripts

o	=	Used to identify a cost item as belonging to the nominal case, as opposed to a variant case

Table 2-1

GASIFIER PLANT CHARACTERISTICS
DATA SUPPORTING USE OF THE HAND METHOD*

Gasifier Rates and Conditions	Nominal Cases*		
	Case 1	Case 2	Case 3
(1) Oxygen blast/gaseous carbon, R_{oc}:			
$R_{oc} = n_1\ (O_2\ \text{blst})\ n_o(C) =$	0.450	0.365	0.489
(2) Water/gaseous carbon, R_{wc}:			
$R_{wc} = [n_2(H_2O) + n_2(H_2O_d)] \div n_o(C) =$	0.5475	1.193	0.490
(3) Water quench/gas carbon, R_{qc}:			
$R_{qc} = \frac{n_1(qnch)}{n_o(C)} =$	0.1966	0	0
(4) Blast gas (not steam)/gaseous carbon $R_{Bc} = \frac{n_1(N_2,O_2)}{n_1(O_2)} \times R_{oc} =$	0.459	0.372	2.329
(5) Enthalpy, generated steam, ref. (liquid water at 70°F, Btu/lb:			
a. h(stm, blst); sat'd, 900°F, 900°F; 65 psia.	1,133	1,440	1,440
b. h(stm,hp); 900°F; 1,055 psia	1,410	1,410	1,410
(6) $Cp(N_2,O_2)$, Molar heat capacity,			
blast gas:	7.1	7.1	7.1
(7) Cp(Fuel gas, hot) Btu/mol°F=	8.43	8.52	7.96
(8) Cp(Fuel gas, cool) Btu/mol°F =	7.35	7.35	7.1
(9) Cp(slag) Btu/lb°F =	0.25	0.25	0.25
(10) Reactor temperature:			
T(reactor)	>200°F +MP(ASH)	<200°F -SP(ASH)	>200°F -SP(ASH)
(11) Fraction of gaseous carbon which is CO:			
$\alpha =$	0.85	0.672	0.802

*Note: Typical values only; calculate actual values in procedure.
Conversion constant: 3,415.2 Btu = 1 kWhr.

	Case 1	Case 2	Case 3
(12) Fraction of carbon in coal converted to gas:			
γ = Anthracite	0.87	0.83	0.83
γ = Eastern/Midwest coal	0.95	0.89	0.89
γ = Western coal	0.98	0.95	0.95
(13) Energy consumption, grinding and miscellaneous, kW, plant-wide	900	550	550
(14) Fraction of high pressure steam going to process use from 165 psia header R_{ps}	0.34	0.21	0.26
(15) Compression energy:			
(a) Air-to-oxygen plant, Btu/mol	21,296	21,296	21,296
(b) Dry blast to gasifier, Btu/mol	9,218	9,218	9,218
(c) Raw gas compression, Btu/mol	2,676	2,676	2,676
(16) Recovered energy expansion of fuel gas, Btu/mol	1,354	1,354	1,354
(17) Gas treatment section, constants: a:	0.124	0.016	0.160
b:	0.110	0.076	0.294
(18) Capital cost/field cost ratio, (C_8/C_7)	1.355	1.308	1.33
(19) Gas need at Claus plant, Q(Claus) Btu/hr	$1x10^6$	$1x10^6$	$2x10^6$
(20) Gas requirement for drying coal Btu/lb evaporation	3,163	3,163	3,163
(21) Gas treatment pressure, psia	150	150	150
(22) Identification of nominal cases			
Basis			
Blast Mode	O_2/steam	O_2/steam	Air/steam
Gasifier Type	Entrained solids	Fluidized solids	Fluidized solids
Sulfur Content in Coal, %	2	2	2
Sulfur Emission in Gases lb SO_2 per 10^6 Btu HHV of Coal	1.2	1.2	1.2
Gas Treatment Pressure, Optimum, psia	150	150	150

PROCEDURE AND EXAMPLES

A worker using the computation scheme starts with the ultimate analysis of the coal received at the plant and considers the behavior of the gasification process on the basis of 100 lb of this coal. Later, he converts his performance numbers to a basis of one hour's operation of the plant, and still later, to the 25-year basis for finding the costs and life-cycle production of gas.

Table 2-1 is the source of characteristic performance data necessary to several steps in the computation. The values are more or less self-evident in their development, and their validity or replacement with values pertinent to still other schemes of operation is straightforward.

The worker starts with the ultimate analysis of coal and on the basis of 100 lb of coal entering the plant. The subsequent drying of coal to a lower moisture content will be accounted for in the necessary diversion of fuel gas to support drying operations.

The final form for the computation of average gas cost is the same one used in displaying costs in the report. The present prices of coal and electricity are used in computing the recurring annual costs of these items.

The examples attached show the manner of executing the computations.

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS CASE I VARIANT

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr — 250×10^6

Emission Of SO_2:

Product from combustion of fuel gas,
lb $SO_2/10^6$ Btu HHV (coal), 0.6 $e(SO_2)$

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	60.47	W(C)
Hydrogen	3.70	$W(H_2)$
Oxygen	5.96	$W(O_2)$
Nitrogen	1.41	$W(N_2)$
Sulfur	2.00	W(S)
Moisture	5.00	$W(H_2O)$
Ash	21.46	W(Ash)
Total	100	

Ash Softening Temperature = 2500 °F

Ash Melting Temperature = 2650 °F

Note: $W(evap) = W(H_2O) - W_o(H_2O)$

REACTOR PERFORMANCE
Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma =$ 0.95 (1)

Ratio $CO/(CO + CO_2)$, expected value $\alpha =$ 0.85 (2)

Feedstock and resulting char

Carbon: $\dfrac{60.47 \times 0.95/12}{W_o(C) \times (\gamma)/12} =$ $\dfrac{4.787 \text{ Mol}}{n_o(C)}$ (3)

Hydrogen: $\dfrac{3.70\ /2 - 5.96\ /16}{W_o(H_2)/2 - W_o(O_2)/16} =$ $\dfrac{1.478 \text{ Mol}}{n_o(H_2, fc)}$ (4)

Oxygen: $\dfrac{5.96\ /32}{W_o(O_2)/32} =$ $\dfrac{0.186 \text{ Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\dfrac{1.41\ /28}{W_o(N_2)/28} =$ $\dfrac{0.050 \text{ Mol}}{n_o(N_2)}$ (6)

Sulfur: $\dfrac{2.00\ /32}{W_o(S)/32} =$ $\dfrac{0.0625 \text{ Mol}}{n_o(S)}$ (7)

Moisture: $\dfrac{1.94\ /18}{W_o(H_2O)} =$ $\dfrac{0.1078 \text{ Mol}}{n_o(H_2O)}$ (8)

Char: $\dfrac{21.46 + (0.05) \times 60.47}{W_o(Ash) + (1-\gamma) \times W_o(C)} =$ $\dfrac{24.48 \text{ lb}}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ, HHV' coal:

$$\dfrac{4.787 \times (173{,}934) + 1.478 \times (122{,}976) + 0.0625 \times (184{,}640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2, fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} =$$

$\dfrac{1\,025\,920 \text{ Btu}}{HHV' \text{ (coal)}}$ (10)

($\Delta H_c(S)$ = At. wt. x 5,770 Btu/lb)

Heat of combustion @ full conversion, HHV (coal)

$\dfrac{1025\,920 + 0.05263 \times 4.787 \times 173{,}934}{HHV \text{ (coal)} + [1-\gamma)/\gamma] \times n_o(C) \times \Delta H_c(C)} =$ $\dfrac{1\,069\,717 \text{ Btu}}{HHV \text{ (coal)}}$ (11)

Basis: 100 lb coal, with moisture

Blast

Steam:
$$\frac{0.5475 \times 4.787 - [0.108 + 2\times 0.186 + 0.941]}{\underset{(2)^*}{R_{wc}} \times n_o(C) - [n_o(H_2O) + 2N_o(O_2) + \underset{(13)}{n_1 (Quench)}]} = \frac{1.200 \text{ Mol}}{n_1(stm)} \quad (12)$$

Quench:
$$\frac{0.1966 \times 4.787}{\underset{(3)^*}{R_{qc}} \times n_o(C)} = \frac{0.941 \text{ Mol}}{n_1(quench)} \quad (13)$$

Oxygen:
$$\frac{0.450 \times 4.787}{\underset{(1)^*}{R_{oc}} \times n_o(C)} = \frac{2.154 \text{ Mol}}{n_1(O_2blst)} \quad (14)$$

Nitrogen:
$$\frac{[(.459 - .450) : .450] \times 2.154}{[(\underset{(4)^*}{R_{bc}} - \underset{(1)^*}{R_{oc}}) \div R_{oc}] \times n_1(O_2blst)} = \frac{0.0431 \text{ Mol}}{n_1(N_2blst)} \quad (15)$$

Reactor Gases

Carbon monoxide:
$$\frac{0.85 \times 4.787}{\alpha \times n_o(C)} = \frac{4.069 \text{ Mol}}{n_2(CO)} \quad (25)$$

Carbon dioxide:
$$\frac{0.15 \times 4.787}{(1-\alpha) \times n_o(C)} = \frac{0.718 \text{ Mol}}{n_2(CO_2)} \quad (26)$$

Water decomposed:
$$\frac{(2 - 0.85) \times 4.787 - 2\times 2.154}{(2 - \alpha) \times n_o(C) - 2x\underset{(14)}{n_1 (O_2blst)}} = \frac{1.197 \text{ Mol}}{n_2(H_2O_d)} \quad (27)$$

Hydrogen:
$$\frac{1.478 - 0.0625 + 1.197}{n_o(H_2,fc) - n_o(S) + \underset{(27)}{n(H_2O_d)}} = \frac{2.613 \text{ Mol}}{n_2(H_2)} \quad (28)$$

Nitrogen:
$$\frac{0.050 + 0.043}{n_o(N_2) + n_1(N_2blst)} = \frac{0.093 \text{ Mol}}{n_2(N_2)} \quad (29)$$

Sulfur as hydrogen sulfide:
$$\frac{0.0625}{n_o(S)} = \frac{0.0625 \text{ Mol}}{n_2(S)} \quad (30)$$

Water Vapor:
$$\frac{0.1078 + 1.200 + 0.941 + 2\times 0.186 - 1.197}{n_o(H_2O) + n_1(stm) + n_1(qnch) + 2x\underset{(5)}{n_o(O_2)} - \underset{(27)}{n_2(H_2O_d)}}$$

$$\frac{1.424 \text{ Mol}}{n_2(H_2O)} \quad (31)$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

Combustibles:
$$\frac{2\times 4.787 - 2\times 2.154 + 1.478 - 0.0625}{2n_o(C) - 2n_1(O_2blst) + n_o(H_2,fc) - n_o(S)} = \frac{6.682\ \text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$
(14)

Total hot raw gas:
$$\frac{4.787 + 1.4155 + 2.621 + 0.093 + 0.0625}{n_o(C) + n_2(H_2,N,fg) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)} = \frac{8.979\ \text{Mol}}{\Sigma n_i} \quad (33)$$
(41) (42)

Heat Effects

Heating value of fuel gas, excepting H_2S:
$$\frac{6.682 \times 122{,}157}{n_o(H_2,CO) \times \Delta H_c\ (H_2,CO)} = \frac{816{,}620\ \text{Btu}}{Q_c\ (\text{Sweet Gas})} \quad (34)$$
(32)

Heat release in reactor:
$$\frac{4.787 \times 173{,}934 - [4.787 - 2.153] \times [2 \times 122{,}157]}{n_o(C) \times \Delta H_c(C) - [n_o(C)-n_1(O_2)] \times [2\Delta H_c\ (H_2,CO)]} = \frac{189\,099\ \text{Btu}}{Q(\text{reactor})} \quad (35)$$
(14) (32)

Heat release in combustion of H_2S:
$$\frac{0.0625 \times 241{,}092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \frac{15\,068\ \text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:
$$\frac{816\,620 + 189\,099 + 15068}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \frac{1020\,800\ \text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:
$$\frac{173{,}934 \times 4.787 \times [(1-.95)/.95]}{\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]} \quad \frac{43\,822}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$n_o(H_2,fc) - n_o(S) =$ $\underline{1.4155}$ $n_2(H_2,n,fg)$ (41)

$n_2(H_2O) + n_2(H_2O_d) =$ $\underline{2.621}$ $n_{1,2}(H_2O)$ (42)
(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{1{,}200 \times 18 \times 1133}{\underset{(12)}{n_1(stm)} \times 18 \times \underset{(5a)^*}{h(stm)}} \qquad \frac{24\,473 \text{ Btu}}{Q_1\ (stm)} \quad (50)$$

Heat addition to reactor as blast gas (N_2,O_2), Btu:

$$\frac{[2.154 + 0.043] \times 7.1(220-70°F) =}{\underset{(14)}{[n_1(O_2) + n_1(N_2)]} \times \underset{(6)^*}{C_p}(T_{in}-70°F)} \qquad \frac{2340 \text{ Btu}}{Q_1(N_2,O_2)} \quad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - 3.06) \times 0.25 \times (250 - 70) =}{(100\text{ lb} - \underset{**}{W_{evap}}) \times C'_p \times (T_{coal} - 70)} \qquad \frac{4362 \text{ Btu}}{Q_o(coal)} \quad (52)$$

Heat loss from reactor as hot slag:

$$\frac{24.48 \times 0.25 \times (2000-70) =}{\underset{(9)}{W(slag)} \times C'_p \times (T_{slag} - 70)} \qquad \frac{11813 \text{ Btu}}{Q(slag)} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{8.979 \times 7.35 \times (350-70) =}{\underset{(33)}{(\Sigma n_i)} \times \underset{(8)^*}{C_p(CFG)} \times (350 - 70)} \qquad \frac{18479 \text{ Btu}}{Q(CFG)} \quad (54)$$

Total heat release to hot raw product gas:

$$\frac{189\,099 + 24\,473 + 2\,340 + 4\,362 - 11\,813}{Q(retr) + Q_1(stm) + Q(N_2,O_2) + Q(coal) - Q(char)} \quad \frac{=208447 \text{ Btu}}{Q(HFG)} \quad (55)$$

Temperature reached in reactor:

$$\frac{208447/[8.43 \times 8.979] + 70}{Q(HFG)/[\underset{(7)^*}{C_p(HFG)} \times \Sigma n_i] + 70} \qquad \frac{2824}{T(retr)} \quad (56)$$

Case 1: This temperature should be at least 2800°F
Cases 1,2, &3: See Item (10), Table 2-1.

*See Table 2-1.

**See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\frac{[208447 - 18479 - 24473] : 1410}{[Q(HFG) - Q(CFG) - Q_l(Stm)] : h(stm, hp)} = \frac{117.4 \text{ lb}}{W_3(stm, hp)} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\quad] : \quad}{[Q(HFG) - Q(CFG)] : h(stm, hp)} = \frac{\text{lb}}{W_3(stm, hp)} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\quad - \quad - \quad] : \quad}{[Q(HFG) - Q(CFG) - Q_l(N_2, O_2)] : h(stm, hp)} = \frac{\quad}{W_3(stm, hp)} \quad (59)$$

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ENERGY MANAGEMENT

Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21{,}296 \times 2.154}{21{,}296 \times n_1(O_2)} = \frac{45\ 872 \text{ Btu}}{E_c(\text{AIR})} \quad (60)$$

(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9{,}218 \times \underline{\qquad}}{9{,}218 \times n_1(O_2)} = \frac{\underline{\qquad} \text{ Btu}}{E_c(\text{AIR})} \quad (61)$$

(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2{,}676 \times [8.979 - 1.424]}{2{,}676 \times [\Sigma n_i - n_2(H_2O)]} = \frac{20\ 230 \text{ Btu}}{E_c(\text{FG})} \quad (63)$$

(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1{,}354 \times [8.979 - 1.424]}{1{,}354 \times [\Sigma n_i - n_2(H_2O)]} = \frac{10\ 236 \text{ Btu}}{E_x(\text{FG})} \quad (64)$$

(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(117.4) \times [327 + 149 \times .343] - 322\ [117.4 \times .343 + 0.0]}{W(\text{stm,hp}) \times [327 + 149 \times \text{Rps}] - 332\ [W(\text{stm,hp}) \times \text{Rps} + W_1(\text{stm})]} =$$

(14)*

$$\frac{31\ 019 \text{ Btu}}{E_x(\text{stm})} \quad (65)$$

Where $W_1(\text{stm}) = 18 \times n_1(\text{stm})$ lb ; this value to be entered for Cases 2 & 3 only
(12)

*See Table 2-1.

PLANT SCALE PERFORMANCE
COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [816\,620 + 15068]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [Q_c(H_2,CO) + Q_c(H_2S)]} = \frac{30060 \text{ lb/hr}}{W(\text{Coal})} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
Item Sub i	Lb	n_i Mols	N_i Mols	Mol/Fract.	Mol/wt.	Lb
	71_i	72_i	73_i	74_i	75_i	76_i
Feed						
(70) a Coal	•100		•	–	NA	•30060
Blast				–		
(12) b Stm	21.62	1.200	361		18.016	6504
(14) c O_2	68.93	2.154	647		32.000	20764
(15) d N_2	1.16	0.0431	13		28.010	364
e(SubΣ)	• 91.72	3.397	•1021	NA	NA	•27572
(13) f Quench	• 16.95	0.944	• 283	NA	18.016	• 5096
g Total	• 208.68	4.340	•1304	NA	NA	•62728
Effluent						
* h Evapn	• 3.06		•	–	NA	• 920
Sour Gas				–		
(25) j CO	113.97	4.069	1223	0.538	28.010	34526
(26) k CO_2	31.60	0.718	216	0.095	44.010	9506
(28) l H_2	5.27	2.613	786	0.346	2.016	1585
(29) m N_2	2.61	0.093	28	0.0123	28.016	784
(30) n (H_2S)	2.13	0.0625	19	0.0083	34.076	644
o Dry FG	155.58	7.5555	2271	1.000		46775
(31) p H_2O	25.65	1.424	428	--	18.016	7710
(33) q (HFG)	• 181.26	8.979	•2699	–		•54486
(9) r Char	• 24.48		•	–	NA	• 7358
s Total	• 208.80		•	--	NA	•62764

Note: $73i/72i = 76i/71i = W(\text{Coal})/100$
$71i/72i = 76i/73i = 75i$

*See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source	Component		Btu	kWhr	Btu	kWhr
Item	Sub.		80_i	81_i	82_i	83_i
Compression						
(60)	a	Oxy plant	45 872	13.432	13.791×10^6	4038
(61)	b	Air blast	—	—	—	—
(63)	c	Raw fuel gas	20 230	5.924	6.081	1781
(13)*	d	Misc.	10 225	2.994	3.074	900
	e	Total	• 76 327	• 22.350	• 22.946×10^6	• 6719
Recovery Expansion						
(64)	f	Fuel gas	10 236	2.997	3.077	901
(65)	g	Steam	31 020	9.083	9.324	2732
	h	Total	• 41 255	• 12.080	• 12.401×10^6	• 3633
Net Demand						
(e,h)	j	Electric pwr	• 35 071	• 10.270	• 10.542×10^6	• 3 086
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas	816 620		245.476×10^6	
(36)	l	H_2S	15 068		4.529	
(35)	m	Reactor	189 099		56.843	
(38)	n	Char	43 822		13.172	
	o	Total	• 1064 609		• 320.020×10^6	
(11)	p	Coal	• 1 069 717		• 321.557×10^6	
Total Energy to Plant						
(j,p)	q		• 1 104 788		• 332.099×10^6	

Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$

$81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$

*See Table 2-1.

PLANT COSTS

Capital Costs $1000

Oxygen/Air Plant: (85)

$$\frac{[(647+13)/(648+13)]^{0.6}}{[(N_c + N_d) / (N_c^o + N_d^o)]^{0.6}} \quad \frac{\times \; 7064}{\times \; c_1^o} = \frac{7064}{C_1}$$

(73_c) (73_d) (See Note)

Gasification Module:

$$\frac{[2649/2738] \times 5426}{[N_q / N_q^o] \times C_2^o} = \frac{5379}{C_2} \qquad (86)$$

(73_q) (see note)

Compression/Expansion:

$$\frac{(2271/2216) \times 1706}{(N_o/N_o^o) \times C_3^o} = \frac{1748}{C_3} \qquad (87)$$

(73_o) (see note)

Gas Treatment Module:

$$\frac{\{1 + .124 \times [2.00 - 2.00]\} \times \{1 - .110 \times \ln[0.60 / 1.2] \times 2303}{\{1 + a \times [W_o(S) - W_o^o(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^o(SO_2)] \times C_4^o} =$$

(17a)* (7) (17b)* (See Design Basis)

$$\frac{2478}{C_4} \qquad (88)$$

*See Table 2-1.

Note: Values for C^o, for the nominal cases, are in the Final Report, Appendix F.

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Coal Preparation Module: $1,000

$$\frac{[30060 / 30100]^{.5} \times 2850}{[W(\text{Coal}) / W^{o}(\text{Coal})]^{.5} \times C_5^{o}} = \underset{C_5}{2846} \quad (89)$$

Utilities, Piping, Waste Disposal: constant $\underset{C_6}{2727}$ (90)

Direct Field Cost: $\underset{C_7}{22\,124}$ (91)

Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$

Total Capital Cost (92)

$$\frac{22\,124 \times (1.355)}{C_7 \times (C_8/C_7)} = \underset{C_8}{29\,978}$$

(18)*

Operating Costs, Annual, Based on 90% Service Factor $1,000

Coal @ W(Coal) lb/hr: (96)

$$\frac{(30\,060 / 2{,}000) \times (7{,}889 \text{ hr/yr}) \quad 25}{(W(\text{Coal})/ 2{,}000) \times (7{,}889 \text{ hr/yr}) \times (\$/\text{ton})} = \underset{0(\text{coal})}{2964}$$

Electric power @ E_D kW: (97)

$$\frac{3086 \times 7889 \times 0.030}{(E_D) \times (7{,}889 \text{ hr/yr}) \ (\$/\text{kWhr})} = \underset{0(\text{pwr})}{730}$$

(83)

Catalyst, Chemicals, from Nominal Case:
Equipment, Supplies, Utilities
Operating Personnel
Maintenance Materials and Labor

From Report, Subtotal, 0^{o}(Misc) = $\underset{0(\text{Misc})}{1488}$ (98)

*See Table 2-1.

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Fuel Gas Production over 25 Years, based on hourly rates

$$[\ 245.5\times10^6 - 920 \times 3{,}163 - 1\times10^6\ ] \times 0.197 \times 10^6 =$$

$$[Q_c(\text{Sweet Gas}) - W_o(\text{evap}) \times 3{,}163 - Q(\text{Claus})] \times 0.197 \times 10^6$$

(82k) (76h) (20) (19)*

47.59×10^{12} BTU (99)

$\Sigma Q(PG)$

Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^o, are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars: One Time	Amount, Thousands of Dollars: Recurring	Discount Factor	Discounted Cost, Thousands of Dollars
(1)	First-Year Construction	+0	2	5 096	17%	0.867	4 418
(2)	Second-Year Construction	+0	3	10 193	34%	0.788	8 032
(3)	Third-Year Construction	+0	4	14 689	49%	0.717	10 532
(4)	● Total Investment			● 29 978			● 22 982
(5)	Coal	+5	5-29		2964	12.268	36 362
(6)	Electricity	+6	5-29		730	14.057	10 262
(7)	Operating Labor and Materials	+0	5-29		1488	6.505	9 679
(8)	● Total Operating Costs				● 5182		● 56 303
(9)	● Total Project Costs						● 79 285
(10)	Fuel Oil Alternative	+8	5-29		4 765	18.631	88 772
(11)	Energy Available over 25 years, billions of Btu						47 592
(12)	Product Gas Unit Cost, $/million Btu (line 9 divided by line 11)						1.67
(13)	Fuel Oil Alternative Unit Cost, $ million Btu (line 10 divided by line 11)						1.87
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						1.32

Cost of gas from GASPLANT program, $/10^6 Btu 1.63

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WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS CASE 2 VARIANT

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr — 250×10^6

Emission Of SO_2:

Product from combustion of fuel gas,
lb $SO_2/10^6$ Btu HHV (coal), 0.60 $e(SO_2)$

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	60.47	$W(C)$
Hydrogen	3.70	$W(H_2)$
Oxygen	5.96	$W(O_2)$
Nitrogen	1.41	$W(N_2)$
Sulfur	2.00	$W(S)$
Moisture	5.00	$W(H_2O)$
Ash	21.46	$W(Ash)$
Total	100	

Ash Softening Temperature = 2500 °F

Ash Melting Temperature = 2650 °F

Note: $W(evap) = W(H_2O) - W_o(H_2O)$

REACTOR PERFORMANCE
Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction γ = 0.89 (1)

Ratio $CO/(CO + CO_2)$, expected value α = 0.612 (2)

Feedstock and resulting char

Carbon: $\dfrac{60.47 \times 0.89 / 12}{W_o(C) \times (\gamma)/12}$ = $\dfrac{4.485 \text{ Mol}}{n_o(C)}$ (3)

Hydrogen: $\dfrac{3.70/2 - 5.96/16}{W_o(H_2)/2 - W_o(O_2)/16}$ = $\dfrac{1.478 \text{ Mol}}{n_o(H_2, fc)}$ (4)

Oxygen: $\dfrac{5.96/32}{W_o(O_2)/32}$ = $\dfrac{0.1863 \text{ Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\dfrac{1.41/28}{W_o(N_2)/28}$ = $\dfrac{0.0504 \text{ Mol}}{n_o(N_2)}$ (6)

Sulfur: $\dfrac{2.00/32}{W_o(S)/32}$ = $\dfrac{0.0625 \text{ Mol}}{n_o(S)}$ (7)

Moisture: $\dfrac{5.00/18}{W_o(H_2O)}$ = $\dfrac{0.278 \text{ Mol}}{n_o(H_2O)}$ (8)

Char: $\dfrac{21.46 + (1-.89) \times 60.47}{W_o(Ash) + (1-) \times W_o(C)}$ = $\dfrac{28.11 \text{ lb}}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ, HHV' coal:

$$\dfrac{4.485 \times (173{,}934) + 1.478 \times (122{,}976) + 0.0625 \times (184{,}640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2, fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} =$$

$\dfrac{973\,305 \text{ Btu}}{\text{HHV' (coal)}}$ (10)

($\Delta H_c(S)$ = At. wt. x 5,770 Btu/lb)

Heat of combustion @ full conversion, HHV (coal)

$$\dfrac{973\,305 + [(1-0.89)/0.89] \times 4.485 \times 173{,}934}{\text{HHV (coal)} + [1-\gamma)/\gamma] \times n_o(C) \times \Delta H_c(C)} = \dfrac{1\,069\,718 \text{ Btu}}{\text{HHV (coal)}} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

Steam:
$$R_{wc} \times n_o(C) - [n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})] = n_1(\text{stm}) \text{ Mol} \quad (12)$$
(2)* (13)

$$1.193 \times 4.485 - [0.278 + 2 \times 0.1863 + 0.0] = 4.700$$

Quench:
$$R_{qc} \times n_o(C) = n_1(\text{quench}) \text{ Mol} \quad (13)$$
(3)*

$$0.0 \times 4.485 = \text{—0—}$$

Oxygen:
$$R_{oc} \times n_o(C) = n_1(O_2\text{blst}) \text{ Mol} \quad (14)$$
(1)*

$$0.365 \times 4.485 = 1.637$$

Nitrogen:
$$[(R_{bc} - R_{oc}) \div R_{oc}] \times n_1(O_2\text{blst}) = n_1(N_2\text{blst}) \text{ Mol} \quad (15)$$
(4)* (1)*

$$[(.372 - .365) \div .365] \times 1.637 = 0.0314$$

Reactor Gases

Carbon monoxide:
$$\alpha \times n_o(C) = n_2(CO) \text{ Mol} \quad (25)$$

$$.672 \times 4.485 = 3.014$$

Carbon dioxide:
$$(1-\alpha) \times n_o(C) = n_2(CO_2) \text{ Mol} \quad (26)$$

$$(1-.672) \times 4.485 = 1.471$$

Water decomposed:
$$(2 - \alpha) \times n_o(C) - 2 \times n_1(O_2\text{blst}) = n_2(H_2O_d) \text{ Mol} \quad (27)$$
(14)

$$(2 - .672) \times 4.485 - 2 \times 1.637 = 2.682$$

Hydrogen:
$$n_o(H_2, fc) - n_o(S) + n(H_2O_d) = n_2(H_2) \text{ Mol} \quad (28)$$
(27)

$$1.478 - 0.0625 + 2.682 = 4.098$$

Nitrogen:
$$n_o(N_2) + n_1(N_2\text{blst}) = n_2(N_2) \text{ Mol} \quad (29)$$

$$0.050 + 0.031 = 0.081$$

Sulfur as hydrogen sulfide:
$$n_o(S) = n_2(S) \text{ Mol} \quad (30)$$

$$0.0625 = 0.0625$$

Water Vapor:
$$n_o(H_2O) + n_1(\text{stm}) + n_1(\text{qnch}) + 2 \times n_o(O_2) - n_2(H_2O_d) = n_2(H_2O) \text{ Mol} \quad (31)$$
(5) (27)

$$0.278 + 4.701 + 0.00 + 2 \times 0.186 - 2.682 = 2.669$$

*See Table 2-1.

Basis: 100 lb coal, with moisture

Combustibles:

2x 4.485 2x 1.637 + 1.478 - 0.0625 =

$2n_o(C) - 2n_1(O_2 blst) + n_o(H_2, fc) - n_o(S)$

(14)

7.112 Mol

N_2(cmbsl) (32)

Total hot raw gas:

4.485 + 1.4155 + 5.351 + 0.081 + 0.0625

$n_o(C) + n_2(H_2, N, fg) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)$

(41) (42)

11.395 Mol

Σn_i (33)

Heat Effects

Heating value of fuel gas, excepting H_2S:

7.112 x 122,157 =

$n_o(H_2, CO) \times \Delta H_c(H_2, CO)$

(32)

868 780 Btu

Q_c (Sweet Gas) (34)

Heat release in reactor:

4.485 x 173,934 - [4.485 - 1.637] x [2 x 122,157] =

$n_o(C) \times \Delta H_c(C) - [n_o(C) - n_1(O_2)] \times [2\Delta H_c(H_2, CO)]$

(14) (32)

84 288 Btu

Q(reactor) (35)

Heat release in combustion of H_2S:

0.0625 x 241,092 =

$n_2(H_2S) \times \Delta H_c(H_2S)$

15 068 Btu

$Q_c(H_2S)$ (36)

Sum of heat release effects:

868 780 + 84 288 + 15 068 =

Q_c(Sweet gas) + Q(reactor) + $Q_c(H_2S)$

968 136 Btu

ΣQ (37)

Heating value of unconverted carbon in char:

173,934 x 4.485 x[(1-.89)/.89]

$\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]$

96 416

Q_c(Char) (38)

Miscellaneous

$n_o(H_2, fc) - n_o(S)$ = 1.4155 $n_2(H_2, n, fg)$ (41)

$n_2(H_2O) + n_2(H_2O_d)$ = 5.351 $n_{1,2}(H_2O)$ (42)

(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\underset{(12)}{\frac{4.700}{n_1(stm)}} \times \frac{18}{18} \times \underset{(5a)^*}{\frac{1440}{h(stm)}} \qquad \frac{121\,824 \text{ Btu}}{Q_1(stm)} \quad (50)$$

Heat addition to reactor as blast gas (N_2, O_2), Btu:

$$\underset{(14)}{\frac{[1.637 + 0.031]}{[n_1(O_2) + n_1(N_2)]}} \times \underset{(6)^*}{\frac{7.1(70 - 70°F)}{C_p(T_{in} - 70°F)}} = \qquad \frac{-0- \text{ Btu}}{Q_1(N_2, O_2)} \quad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - 6.0)}{(100\text{ lb} - \underset{**}{W_{evap}})} \times \frac{0.25}{C'_p} \times \frac{(70 - 70)}{(T_{coal} - 70)} = \qquad \frac{-0- \text{ Btu}}{Q_o(coal)} \quad (52)$$

Heat loss from reactor as hot slag:

$$\underset{(9)}{\frac{28.11}{W(slag)}} \times \frac{0.25}{C'_p} \times \frac{(70 - 70)}{(T_{slag} - 70)} = \qquad \frac{-0- \text{ Btu}}{Q(slag)} \quad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\underset{(33)}{\frac{11.395}{(\Sigma n_i)}} \times \underset{(8)^*}{\frac{7.35}{C_p(CFG)}} \times \frac{(350 - 70)}{(350 - 70)} = \qquad \frac{23\,450 \text{ Btu}}{Q(CFG)} \quad (54)$$

Total heat release to hot raw product gas:

$$\frac{84\,288}{Q(rctr)} + \frac{121\,824}{Q_1(stm)} + \frac{0.0}{Q(N_2, O_2)} + \frac{0.0}{Q(coal)} - \frac{0.0}{Q(char)} \qquad \frac{= 206\,112 \text{ Btu}}{Q(HFG)} \quad (55)$$

Temperature reached in reactor:

$$\frac{206\,112}{Q(HFG)} / \left[\underset{(7)^*}{\frac{8.52}{C_p(HFG)}} \times \frac{11.395}{\Sigma n_i}\right] + 70 \qquad \frac{2192}{T(rctr)} \quad (56)$$

Case 1: This temperature should be at least 2800°F
Cases 1,2, &3: See Item (10), Table 2-1.

*See Table 2-1.

**See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\frac{[\quad - \quad - \quad] : \quad}{[Q(HFG) - Q(CFG) - Q_1(Stm)] : h(stm, hp)} = \frac{\quad lb}{W_3(stm, hp)} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 2 only:

$$\frac{[206112 - 23450] : 1410}{[Q(HFG) - Q(CFG)] : h(stm, hp)} = \frac{129.55 \ lb}{W_3(stm, hp)} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\quad - \quad - \quad] : \quad}{[Q(HFG) - Q(CFG) - Q_1(N_2, O_2)] : h(stm, hp)} = \frac{\quad}{W_3(stm, hp)} \quad (59)$$

ENERGY MANAGEMENT
Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\underset{\text{(15a)*}}{\frac{21{,}296 \times 1.637}{21{,}296 \times n_1(O_2)}} = \frac{34\,862}{E_c(\text{AIR})}\ \text{Btu} \qquad (60)$$

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9{,}218 \times 0.0}{\underset{\text{(15b)*}}{9{,}218} \times \underset{(14)}{n_1(O_2)}} = \frac{-0-}{E_c(\text{AIR})}\ \text{Btu} \qquad (61)$$

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2{,}676 \times [11.395 - 2.669]}{\underset{\text{(15c)*}}{2{,}676} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}]} = \frac{23\,351}{E_c(\text{FG})}\ \text{Btu} \qquad (63)$$

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1{,}354 \times [11.395 - 2.669]}{\underset{\text{(16)*}}{1{,}354} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}]} = \frac{11\,815}{E_x(\text{FG})}\ \text{Btu} \qquad (64)$$

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(129.55) \times [327 + 149 \times .21] - 322\,[129.55 \times .21 + 8462]}{W(\text{stm,hp}) \times [327 + 149 \times \underset{(14)*}{Rps}] - 332\,[W(\text{stm,hp}) \times Rps + W_1(\text{stm})]} =$$

$$\frac{9290}{E_x(\text{stm})}\ \text{Btu} \qquad (65)$$

Where $W_1(\text{stm}) = 18 \times \underset{(12)}{n_1(\text{stm})}$ lb

*See Table 2-1.

PLANT SCALE PERFORMANCE
COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [868\,780 + 15\,068]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [Q_c(H_2,CO) + Q_c(H_2S)]} = \frac{28{,}285 \text{ lb/hr}}{W(\text{Coal})} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
Item Sub i	Lb	n_i Mols	N_i Mols	Mol/Fract.	Mol/wt.	Lb
	71_i	72_i	73_i	74_i	75_i	76_i
Feed						
(70) a Coal	●100		● NA	–	NA	●28 285
Blast				–		
(12) b Stm	84.68	4.700	1329.7		18.016	23 956
(14) c O_2	52.38	1.637	463.0		32.000	14 816
(15) d N_2	0.88	0.0314	8.8		28.010	246
e(SubΣ)	● 137.94		●	NA	NA	●39 018
(13) f Quench	● —	—	● —	NA	18.016	● —
g Total	● 237.94		●	NA	NA	●67 303
Effluent						
* h Evapn	● -0-	-0-	● -0-	–	NA	● -0-
Sour Gas				–		
(25) j CO	84.42	3.014	852.5	0.345	28.010	23 878
(26) k CO_2	64.74	1.471	416.1	0.169	44.010	18 313
(28) l H_2	8.26	4.098	1159.1	0.479	2.016	2 337
(29) m N_2	2.27	0.081	22.9	0.009	28.016	642
(30) n (H_2S)	2.13	0.0625	17.7	0.007	34.076	603
o Dry FG	161.82	8.7265	2468.3	1.000		45 773
(31) p H_2O	44.08	2.669	754.9	--	18.016	13 600
(33) q (HFG)	● 209.91	11.395	●3223.2	--		●59 373
(9) r Char	● 28.11		●	–	NA	● 7951
s Total	●238.02		●	--	NA	●67 324

Note: 73i/72i = 76i/71i = W(Coal)/100
71i/72i = 76i/73i = 75i

*See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source Item	Component Sub.		Btu	kWhr	Btu	kWhr
			80_i	81_i	82_i	83_i
Compression						
(60)	a	Oxy plant	34 862	10,208	9.86×10^6	2887
(61)	b	Air blast	—	—	—	—
(63)	c	Raw fuel gas	23 351	6.837	6.605	1934
(13)*	d	Misc.	6 641	1.945	1.878	550
	e	Total	• 64 854	• 18.990	• 18.343×10^6	• 5371
Recovery Expansion						
(64)	f	Fuel gas	11 815	3.460	3.343	979
(65)	g	Steam	9 290	2.720	2.626	769
	h	Total	• 21 105	• 6.180	• 5.969×10^6	• 1 748
Net Demand						
(e,h)	j	Electric pwr	• 43 749	• 12.810	• 12.374×10^6	• 3 623
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas	868 780		245.737×10^6	
(36)	l	H_2S	15 068		4.262	
(35)	m	Reactor	84 288		23.841	
(38)	n	Char	96 416		27.271	
	o	Total	• 1064 552		• 301.108	
(11)	p	Coal	• 1 069 718		• 302.570×10^6	
Total Energy to Plant						
(j,p)	q		• 1 113 467		• 314.944×10^6	

Note: $82_i/80_i = 83_i/81_i = W(\mathrm{Coal})/100$

$81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$

*See Table 2-1.

Capital Costs $1000

Oxygen/Air Plant: (85)

$$[(463 + 8.8)/(470 + 10)]^{0.6} \times 5992 = 5930$$

$$[(N_c + N_d) / (N_c^\circ + N_d^\circ)]^{0.6} \times c_1^\circ \qquad C_1$$

(73_c) (73_d) (See Note)

Gasification Module:

$$[3223 / 5326] \times 6016 = 5812$$

$$[N_q / N_q^\circ] \times C_2^\circ \qquad C_2 \qquad (86)$$

(73_q) (see note)

Compression/Expansion:

$$(2468 / 2319) \times 1758 = 1871$$

$$(N_o/N_o^\circ) \times C_3^\circ \qquad C_3 \qquad (87)$$

(73_o) (see note)

Gas Treatment Module:

$$\{1 + .016 \times [2.0 - 2.0]\} \times \{1 - .012 \times \ln[0.6 / 1.2]\} \times 3843 =$$

$$\{1 + a \times [W_o(S) - W_o^\circ(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^\circ(SO_2)]\} \times C_4^\circ$$

(17a)* (7) (17b)* (See Design Basis)

$$4045 \qquad (88)$$

$$C_4$$

*See Table 2-1.

Note: Values for C°, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module: $1,000

$[28285 / 29310]^{.5} \times 2228$ = 2189 (89)
$[W(Coal) / W^{o}(Coal)]^{.5} \times C_5^{o}$ = C_5

Utilities, Piping, Waste Disposal: constant 2343 (90)
C_6

Direct Field Cost: (91)
21957
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6$ = C_7

Total Capital Cost (92)

21957 x (1.308) = 28,720
$C_7 \times (C_8/C_7)$ = C_8
(18)*

Operating Costs, Annual, Based on 90% Service Factor $1,000

Coal @ W(Coal) lb/hr: (96)

(28285 / 2,000) x (7,889 hr/yr) 25 = 2789
(W(Coal)/ 2,000) x (7,889 hr/yr) x ($/ton) = 0(coal)

Electric power @ E_D kW: (97)

3623 7889 0.030 = 857
(E_D) x (7,889 hr/yr) ($/kWhr) = 0(pwr)
(83g)

Catalyst, Chemicals, from Nominal Case:
Equipment, Supplies, Utilities
Operating Personnel
Maintenance Materials and Labor 1488 (98)

From Report, Subtotal, 0^{o}(Misc) = $0_{(Misc)}$

*See Table 2-1.

Fuel Gas Production over 25 Years, based on hourly rates

$$[\ 245.7 \quad - \quad 0.0 \quad \times 3{,}163 - 1\times10^{6}\ ] \times 0.197 \times 10^{6} =$$

$$[Q_c(\text{Sweet Gas}) - W_o(\text{evap}) \times 3{,}163 - Q(\text{Claus})] \times 0.197 \times 10^{6}$$

(82k) (20) (19)*

$$\frac{48.2 \times 10^{12}}{\Sigma Q(PG)} \quad (99)$$

Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^o, are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars: One Time	Amount, Thousands of Dollars: Recurring	Discount Factor	Discounted Cost, Thousands of Dollars
(1)	First-Year Construction	+0	2	4 880	17%	0.867	4 230
(2)	Second-Year Construction	+0	3	9 770	34%	0.788	7 700
(3)	Third-Year Construction	+0	4	14 070	49%	0.717	10 090
(4)	● Total Investment			● 28 720			● 22 020
(5)	Coal	+5	5-29		2789	12.268	34 220
(6)	Electricity	+6	5-29		857	14.057	12 050
(7)	Operating Labor and Materials	+0	5-29		1488	6.505	9 680
(8)	● Total Operating Costs				● 5134		● 55 950
(9)	● Total Project Costs						● 77 970
(10)	Fuel Oil Alternative	+8	5-29		4 820	18.631	89 801
(11)	*Energy Available over 25 years, billions of Btu*						48 200
(12)	Product Gas Unit Cost, $/million Btu (line 9 divided by line 11)						1.62
(13)	Fuel Oil Alternative Unit Cost, $ million Btu (line 10 divided by line 11)						1.86
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						1.54

Cost of gas from GASPLANT program, $/10^6 Btu 1.62

Section 3

BOILER DERATING

SUMMARY

This section contains the pertinent data and computational worksheets for boiler derating estimate analyses when changing boilers to coal-derived gas fuels. The methods result in estimated derating factors for boiler efficiency steam capacity and combustion product flow rates resulting from the fuel change.

SYSTEM DATA AND NOMENCLATURE

Definition of Typical Boilers

Three types of boilers are included in this study:

- Water tube boilers up to 200,000 lb/hr of steam production
- Fire tube boilers up to 10,000 lb/hr of steam production
- Stoker feed, coal-fired water tube boilers up to 200,000 lb/hr of steam production

The representative (or standard) boiler configuration for each boiler type is assumed to be rated at the maximum capacity stated above. It is assumed that the rating change factors defined for the maximum capacity boiler for each boiler type will generally apply to lower capacity boilers of that type.

All boilers are used for heating service, generating saturated steam at maximum pressures of 150 psig and minimum of 80 psig. No units

deliver superheated steam. The oldest boilers were installed in 1942, and the majority of all boilers were installed in the 1940's. They are predominantly fueled with oil ranging from No. 6 Venezuelan crude to No. 2 diesel with limited natural gas.

Based on the above information, additional general assumptions for these boiler designs can be made. Saturation pressures at 150 psig correspond to steam temperatures of 366^{o}F. These conditions along with the age of boilers support an assumption of natural steam circulation in the boilers. The low steam temperatures, boiler age, and heating application to military bases support an assumption that air preheaters are not used with the subject boilers.

Water Tube Boiler. The standard boiler of this type is assumed to be oil-fired and to deliver saturated steam at 150 psig and 366^{o}F. It is assumed that no air preheaters are used and that the boiler probably was field erected in the 1940's, although today it would be bought as a packaged unit.

Based on relative heat absorption data, the heat transferred to steam by radiation to the water walls and by convection to the boiler tube banks are approximately equal. For this boiler, the total heat transfer is assumed to be 0.5 by radiation and 0.5 by convection.

Fire Tube Boiler. The standard fire tube boiler is assumed to be oil-fired and working with steam conditions of 100 psig and 338^{o}F. This boiler is assumed to function without an air preheater and to have been field erected in the early 1940's. Heat transfer in fire tube boilers is expected to be greater by the convection mode rather than the radiant mode. This is based on the more compact designs for fire tube boilers with combustion product flow being forced through the tubing at greater velocities than in water tube boilers. The total heat transfer in this unit is assumed to be 0.4 by radiation and 0.6 by convection.

Stoker Feed, Coal-Fired Water Tube Boiler. This boiler is assumed to be similar in requirements to the oil-fired, water tube boiler, except for the coal-firing. Steam conditions are again assumed to be 150 psig and 366^{o}F. No air preheaters are used, and the unit is assumed to have been field erected in the 1940's. Total heat transfer in this unit is assumed to be 0.5 by radiation and 0.5 by convection.

Nomenclature

- q = Heat transfer rate, Btu/sec.
- δ = Stefan-Boltzman constant.
- A = Effective heat transfer area, ft^2.
- T_1 = Temperature of combustion gas, ^{o}R.
- T_2 = Temperature of water walls, ^{o}R.
- e = Effective emissivity of combustion gas.
- U_o = Outer tube wall heat transfer coefficient, Btu/ft^2-hr-^{o}F.
- U_L = Inner tube wall heat transfer coefficient, Btu/ft^2-hr-^{o}F.
- G = Mass velocity or mass flow of gas over the tubes, lb/hr ft^2 of cross-sectional area.
- C_p = Specific heat at constant pressure, Btu/lb-^{o}F.
- k = Conductivity of gas, Btu-ft/ft^2-hr-^{o}F.
- D_o = Outside tube diamter, ft.
- U = Absolute gas viscosity, lb/ft-hr.
- F_a = Arrangement factor.
- T_b = Average bulk absolute temperature of gas, ^{o}R.
- T_f = Average film absolute temperature, ^{o}R.

NOTE: The reference heat transfer is identified by subscript 1 (prior to fuel change) and the new heat transfer case by subscript 2 (after change to low-Btu gas fuel).

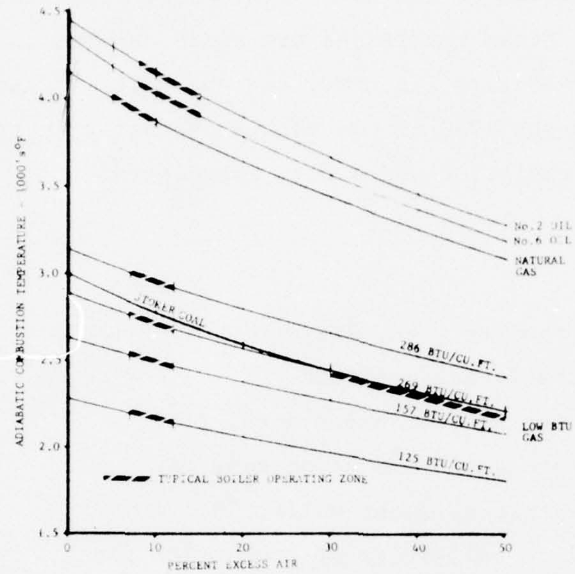

Figure 3-1. Theoretical Adiabatic Combustion Temperature Variation with Percent Excess Air for Various Boiler Fuels

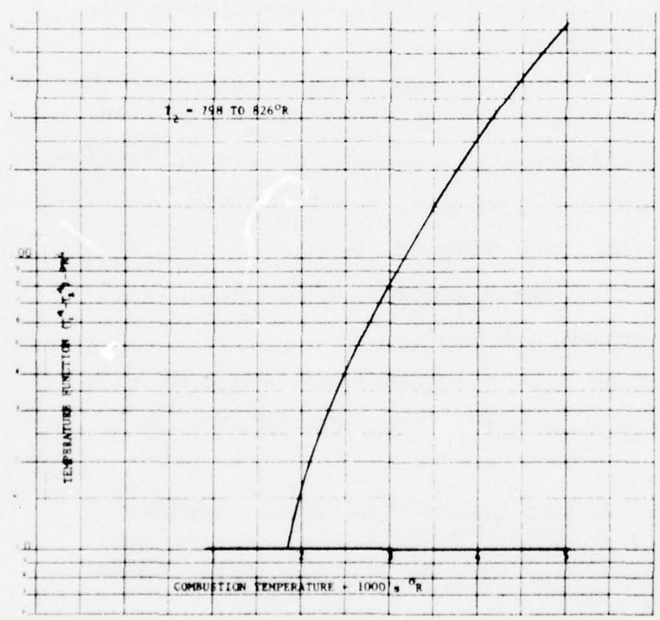

Figure 3-2. Radiant Heat Transfer Function Variation with Combustion Reaction Temperature

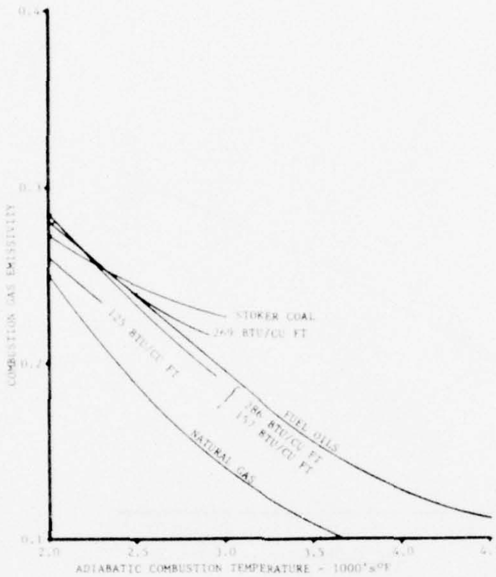

Figure 3-3. Combustion Product Gas Emissivity Variation with Adiabatic Combustion Temperature

Table 3-1

FUEL IN AIR COMBUSTION PRODUCT GAS QUANTITIES

Fuel	Stoichiometric Air/Fuel Ratio	Excess Air (%)	Actual Air/Fuel Ratio	High Heating Value (Btu/lb)	Combustion Gas (lb/lb fuel)	Products Flow (lb/10,000 Btu)
No. 2 Diesel Oil	13.051	12	14.617	19,600	15.617	7.968
No. 6 Residual Oil	12.845	12	14.386	18,600	15.386	8.272
Natural Gas	16.434	8	17.749	23,250	18.749	8.064
Coal, Unit Mine	11.545	40	16.163	10,709	17.163	16.03
Low-Btu Gas, 286 Btu/cu ft	4.6154	10	5.0769	5,280	6.0769	11.51
Low-Btu Gas, 269 Btu/cu ft	4.9349	10	5.4284	5,314	6.4284	12.10
Low-Btu Gas, 157 Btu/cu ft	2.3730	10	2.6103	2,708	3.6103	13.33
Low-Btu Gas, 125 Btu/cu ft	2.3977	10	2.6375	1,921	3.6375	18.94

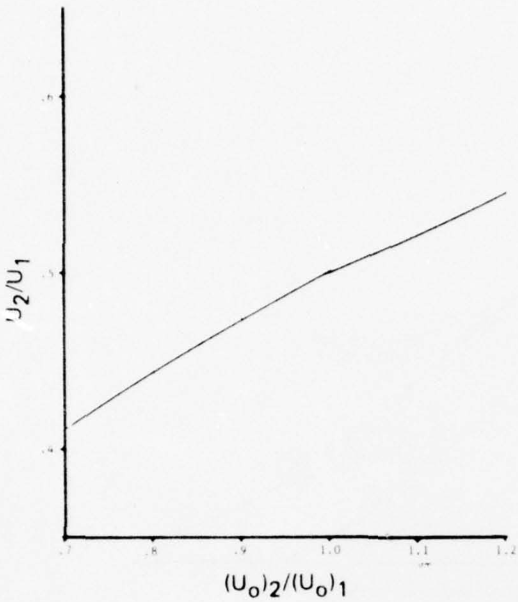

Figure 3-4. Overall Convection Heat Transfer Coefficient Variation with That of the Outer Tube Surface

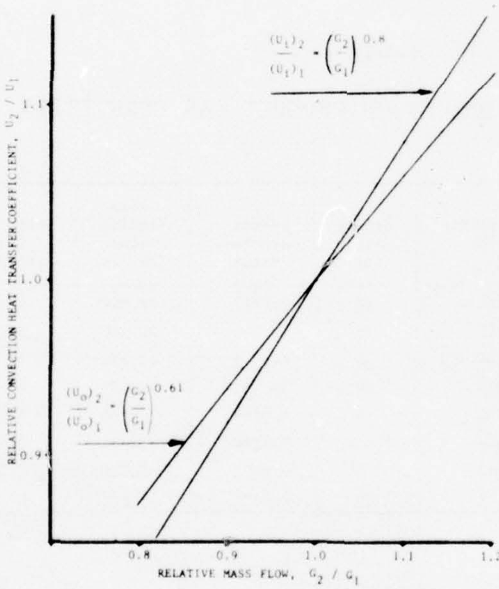

Figure 3-5. Relative Convection Heat Transfer Coefficient Variation with Relative Combustion Products Gas Mass Flow

PROCEDURE AND EXAMPLES

The worksheet shows the computation necessary to estimate the boiler performance rating factors for conversion to the three fuels for each of the three boiler types. The three fuel changes are to low-Btu gases of 286, 269, and 125 Btu/ft^3. Additional worksheets are included.

The computational methodology is best explained by defining each computational step. These definitions are numbered to correspond with those on the worksheet.

1. Boiler Type. Identify the type of boiler by entering the letters WT for water tube or FT for fire tube boilers.

2. Steam Temperature, ^oF. Enter the saturated steam temperature for the boiler being analyzed. In the sample computations, the assumed temperatures are 366^oF for water tube boilers and 338^oF for fire tube boilers.

3. Fuel. Identify the fuel for which the boiler was originally designed.

4. Excess Air, %. Enter the percent of excess air supplied to the furnace section for combustion of the original fuel.

5. Fraction of Heat Transferred by Radiation. Enter the fraction of total heat transferred (steam generated) that occurs in the furnace section of the boiler.

6. Fraction of Heat Transferred by Convection. Enter the fraction of total heat transferred (steam generated) that occurs in the convection tube bundles of the boiler.

7. Check. The sum of 5 and 6 must equal 1.00 to account for all heat transferred in the boiler.

8. Combustion Temperature, ^oF. Enter the temperature from Figure 3-1 as a function of fuel 3 and excess air 4 .

9. Combustion Temperature, R. Add 460 to 8 .

10 Temperature Function. Enter the temperature function from Figure 3-2 as a function of combustion temperature 9 .

11 Emissivity. Enter the emissivity from Figure 3-3 as a function of fuel 3 and combustion temperature 8 .

12 Combustion Products Rate, lb/10,000 Btu. Enter the combustion products rate from Table 3-1 as a function of fuel 3 and excess air 4 .

13 Fuel, Type, and High Heating Value, Btu/cu ft. Enter here the type and high heating value of the coal-derived gas fuel to be burned in the boiler. In the sample computations, gases of 286, 269, and 125 Btu/ft^3 are used.

14 Excess Air, %. Enter the percent of excess air supplied to the furnace air for combustion of the conversion gas to be used in place of the original design fuel. In the sample computations 10 percent excess air is used for all gas fuels.

15 Combustion Temperature, ^oF. Enter the temperature from Figure 3-1 as a function of fuel 13 and excess air 14 .

16 Combustion Temperature, R. Add 460 to 15 .

17 Temperature Function. Enter the temperature function from Figure 3-2 as a function of combustion temperature 16 .

18 Emissivity. Enter the emissivity from Figure 3-3 as a function of fuel 13 and combustion temperature 15 .

19 Combustion Products Rate, lb/10,000 Btu. Enter the combustion products rate from Table 3-1 as a function of fuel 13 and excess air 14 .

20 Ratio of Products. Compute the ratio of combustion products rate with conversion gas fuel to that with the original fuel (19 ÷ 12) . The result indicates the change in combustion products flow rate through the boiler per unit of fuel heat release.

A number greater than 1.00 means an increase in flow rate is required to obtain the same fuel heat release.

Flow rate increases are limited to 1.10 in order to exclude cases requiring major rebuilding of boiler systems to accommodate large gas flow increases.

A number less than 1.00 means a decrease in flow rate is required to obtain the same fuel heat release. For such cases, the ratio used is 1.00, which means that boiler capacity can be increased by injecting additional fuel to maintain the original gas flow rate. This occurs for boilers originally designed for stoker coal-fueling.

21 Compute the ratio of radiant heat transfer with conversion gas fuel to that with the original fuel [(18 / 11) x (17 / 10)]. The result indicates the change in radiant heat transfer performance in the furnace section of the boiler. A number less than 1.00 means that the heat transfer rate is reduced.

22 Compute the ratio of combustion product gas temperature decrease by radiant heat transfer with conversion gas fuel to that with the original fuel (21 / 20). A number less than 1.00 means that the temperature decrease in the furnace is reduced.

23 Stack Temperature, ^{o}F. Enter the measured stack gas temperature or estimate it as the saturated steam temperature plus 100^{o}F for water tube boilers (2 + 100) or + 200^{o}F for fire tube boilers (2 + 200).

24 Compute the approximate temperature decrease of the original fuel combustion gases resulting from radiant heat transfer in the furnace section of the boiler [5 x (8 - 23)].

25 Compute the approximate temperature of the original fuel combustion gases entering the convection tube bundle section of the boiler (8 - 24).

26 Compute the approximate temperature of the conversion gas fuel combustion gas entering the convection tube bundle section of the boiler (15 - 22 x 24).

27 Compute the convection heat transfer driving temperature difference ratio of the conversion gas fuel case to the original fuel case [(26 - 2)/ (25 - 2)].

(28) Enter the relative convection heat transfer coefficient from Figure 3-5. The factor $(U_o)_2/(U_o)_1$ is for water tube boilers. The factor $(U_i)_2/(U_i)_1$ is for fire tube boilers. Both factors are a function of the ratio of products (20) .

(29) Enter the overall convective heat transfer coefficient from Figure 3-4 as a function of $U_o = (U_o)_2/(U_o)_1$ = (28) . This step is required only for water tube boilers.

(30) Compute the overall convective heat transfer coefficients ratio of the conversion gas fuel case to the original fuel case. For water tube boilers, this ratio is (29) /0.5. For fire tube boilers this ratio is (28) .

(31) Compute the ratio of convection heat transfer with conversion gas fuel to that with the original fuel ((30) x (27)). The result indicates the change in convection heat transfer performance in the tube bundle section of the boiler. A number less than 1.00 means that the heat transfer rate is reduced.

(32) Compute the ratio of combustion product gas temperature decrease by convection heat transfer with conversion gas fuel to that with the original fuel ((31) / (20)). A number less than 1.00 means that the temperature decrease in the tube bundle section is reduced.

(33) Compute the total boiler heat transfer performance effect (ratio of steam generation) as ((5) x (21)) + ((6) x (31)). This sums the effects in the radiant furnace and convection tube bundle sections of the boiler.

(34) Compute the total boiler combustion gas temperature decrease effect (ratio of available energy extraction) as ((5) x (22)) + ((6) x (32)).

(35) Compute the temperature increase by combustion in the furnace of the original fuel ((8) - 70.F).

(36) Compute the temperature increase by combustion in the furnace of the conversion gas fuel ((15) - 70.F).

(37) Compute the overall boiler efficiency effect of the fuel change as ((34) x (35))/ (36) . This value indicates the efficiency change expected to occur with the change in boiler fuel. This value times the original fuel boiler efficiency estimates the boiler efficiency with the conversion gas fuel.

Table 3-2

ESTIMATING PROCEDURE WORKSHEET FOR EFFECTS OF FUEL CHANGES ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	–	G	H	I	
1	BOILER TYPE, WT WATER TUBE, FT FIRE TUBE		WT	WT	WT	WT	WT	WT	FT	FT	FT	
2	STEAM TEMPERATURE	F	366	366	366	366	366	366	338	338	338	
	INITIAL CONDITIONS											
3	FUEL		Oil	Oil	Oil	Coal	Coal	Coal	Oil	Oil	Oil	
4	EXCESS AIR	%	12	12	12	40	40	40	12	12	12	
5	FRACTION OF HEAT TRANSFERRED BY RADIATION		.50	.50	.50	.50	.50	.50	.40	.40	.40	
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION		.50	.50	.50	.50	.50	.50	.60	.60	.60	
7	CHECK, 5 + 6 = 1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
8	COMBUSTION TEMPERATURE, F(3 AND 4)	F	3980	3980	3980	[illegible]	[illegible]	[illegible]	3980	3980	3980	
9	COMBUSTION TEMPERATURE, 8 + 460	R	4440	4440	4440	[illegible]	[illegible]	[illegible]	4440	4440	4440	
10	TEMPERATURE FUNCTION, F 9		375	375	375	60	[illegible]	60	375	375	375	
11	EMISSIVITY, F(3 AND 8)		.128	.128	.128	.254	[illegible]	.254	.128	.128	.128	
12	COMBUSTION PRODUCTS RATE, F(3 AND 4)	lb/10,000 BTU	8.272	8.272	8.272	[illegible]	[illegible]	[illegible]	8.272	8.272	8.272	
	NEW FUEL CONDITIONS		MBTU	MBTU	LBTU	MBTU	MBTU	LBTU	MBTU	MBTU	LBTU	
13	FUEL GAS HIGH HEATING VALUE	BTU/CU.FT.	286	269	125	286	269	125	286	269	125	
14	EXCESS AIR	%	10	10	10	10	10	10	10	10	10	
15	COMBUSTION TEMPERATURE, F(13 AND 14)	F	2950	2710	2170	2950	2710	2170	2950	2710	2170	
16	COMBUSTION TEMPERATURE, 15 + 460	R	3410	3170	2630	3410	3170	2630	3410	3170	2630	
17	TEMPERATURE FUNCTION, F 16		133	101	49	133	101	49	133	101	49	
18	EMISSIVITY, F(13 AND 15)		.192	.221	.246	.192	.221	.246	.192	.221	.246	
19	COMBUSTION PRODUCTS RATE, F(13 AND 14)	lb/10,000 BTU	11.51	12.10	18.94	11.51	12.10	18.94	11.51	12.10	18.94	
20	RATIO OF PRODUCTS 19 ÷ 12 ≤ 1.10		(1.39)	(1.46)	(2.29)	(.718)	(.755)	(1.18[illegible])	(1.39)	(1.46)	([illegible])	
			1.10	1.10	1.10	1.00	1.00	1.10	[illegible]	[illegible]	1.10	

Table 3-2 (Continued)

STEP NO	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	F	G	H	I	
	EFFECTS ON RADIANT HEAT TRANSFER											
21	$\left(\frac{q_2}{q_1}\right)_r = \frac{18}{11} \times \frac{17}{10}$		.532	.465	.251	1.676	1.465	.791	.512	.447	.292	
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{21}{20}$		.484	.423	.228	1.676	1.465	.719	.465	.406	.220	
23	STACK TEMPERATURE,											
	WATER TUBE = 2 + 100	F	466	466	466	466	466	466				
	FIRE TUBE = 2 + 200	F							538	538	538	
24	ΔT_r = 5 × (8 − 23)	F	1757	1757	1757	917	917	917	1377	1377	1377	
25	T_{fb1} = 8 − 24	F	2223	2223	2223	1383	1383	1383	2603	2603	2603	
26	T_{fb2} = 15 − 22 × 24	F	2100	1967	1769	1413	1367	1511	2310	2151	1867	
	EFFECTS ON CONVECTIVE HEAT TRANSFER											
27	$\frac{T_{fb2} - T_s}{T_{fb1} - T_s} = \frac{26 - 2}{25 - 2}$		.934	.862	.756	1.029	.984	1.126	.871	.800	.675	
28	$(U_e)_2 / (U_e)_1$, F 20		1.06	1.06	1.06	1.00	1.00	1.06				
	$(U_i)_2 / (U_i)_1$, FOR FIRE TUBE								1.078	1.078	1.078	
29	U_2, F 28		.512	.512	.512	.500	.500	.512	—	—	—	
30	U_2 / U_1,											
	WATER TUBE = 29 ÷ 0.5		1.024	1.024	1.024	1.000	1.000	1.024				
	FIRE TUBE = 28								1.078	1.078	1.078	
31	$\left(\frac{q_2}{q_1}\right)_c$ = 30 × 27		.956	.883	.774	1.029	.984	1.153	.939	.862	.728	
32	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{31}{28}$		.869	.803	.704	1.029	.984	1.048	.854	.784	.662	

Table 3-2 (Continued)

STEP NO.	COMPUTATIONAL STEP	UNITS	A	B	C	D	E	F	G	H	I	
	TOTAL PERFORMANCE EFFECTS											
33	$\left(\frac{q_2}{q_1}\right)_{TOTAL} = (5 \times 21) + (6 \times 31)$		.744	.674	.512	1.352	1.224	.972	.768	.696	.534	
34	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_{TOTAL} = (5 \times 22) + (6 \times 32)$		.676	.613	.466	1.352	1.224	.884	.[illegible]78	.633	.485	
35	$\Delta T_{comb\,1} = 8 - 70$	F	3910	3910	3910	2230	2230	2230	[illegible]910	3910	3910	
36	$\Delta T_{comb\,2} = 15 - 70$	F	2880	2640	2100	2880	2640	2100	288[illegible]	2640	2100	
37	$\left(\frac{EFF.\ 2}{EFF.\ 1}\right)_{TOTAL} = \frac{34 \times 35}{36}$		.918	.908	.868	1.047	1.034	.939	.948	.938	.9[illegible]3	

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr — 250×10^6

Emission Of SO_2:

Product from combustion of fuel gas,
lb $SO_2/10^6$ Btu HHV (coal), ______ $e(SO_2)$

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	______	$W(C)$
Hydrogen	______	$W(H_2)$
Oxygen	______	$W(O_2)$
Nitrogen	______	$W(N_2)$
Sulfur	______	$W(S)$
Moisture	______	$W(H_2O)$
Ash	______	$W(Ash)$
Total	100	

Ash Softening Temperature = ______ °F

Ash Melting Temperature = ______ °F

Note: $W(evap) = W(H_2O) - W_o(H_2O)$.

REACTOR PERFORMANCE
Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma =$ ________ (1)

Ratio $CO/(CO + CO_2)$, expected value $\alpha =$ ________ (2)

Feedstock and resulting char

Carbon: $\dfrac{\quad x \quad /12}{W_o(C) \times (\gamma)/12} =$ $\dfrac{\text{Mol}}{n_o(C)}$ (3)

Hydrogen: $\dfrac{\quad /2 - \quad /16}{W_o(H_2)/2 - W_o(O_2)/16} =$ $\dfrac{\text{Mol}}{n_o(H_2, fc)}$ (4)

Oxygen: $\dfrac{\quad /32}{W_o(O_2)/32} =$ $\dfrac{\text{Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\dfrac{\quad /28}{W_o(N_2)/28} =$ $\dfrac{\text{Mol}}{n_o(N_2)}$ (6)

Sulfur: $\dfrac{\quad /32}{W_o(S)/32} =$ $\dfrac{\text{Mol}}{n_o(S)}$ (7)

Moisture: $\dfrac{\quad /18}{W_o(H_2O)} =$ $\dfrac{\text{Mol}}{n_o(H_2O)}$ (8)

Char: $\dfrac{\quad + (\quad) x \quad}{W_o(Ash) + (1-\gamma) x\, W_o(C)} =$ $\dfrac{\text{lb}}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ, HHV' coal:

$$\frac{\quad x(173{,}934) + \quad x(122{,}976) + \quad x(184{,}640)}{n_o(C) \times \Delta H_c(C) + n_o(H_2, fc) \times \Delta H_c(H_2) + n_o(S) \times \Delta H_c(S)} =$$

$\dfrac{\text{Btu}}{\text{HHV}'\ (\text{coal})}$ (10)

($\Delta H_c(S)$ = At. wt. x 5,770 Btu/lb)

Heat of combustion @ full conversion, HHV (coal)

$$\frac{\quad + \quad x \quad x\ 173{,}934}{\text{HHV (coal)} + [1-\gamma)/\gamma] \times n_o(C) \times \Delta H_c(C)} = \frac{\text{Btu}}{\text{HHV (coal)}} \quad (11)$$

Basis: 100 lb coal, with moisture

Blast

Steam: $\dfrac{\_\_\_ \; x \; \_\_\_ \; - \; [\_\_\_ \; + \; \_\_\_ \; + \; \_\_\_]}{R_{wc} \; x \; n_o(C) \; - \; [n_o(H_2O) \; + \; 2N_o(O_2) \; + \; n_1 \; (\text{Quench})]} =$
(2)* (13)

$\dfrac{\text{Mol}}{n_1(\text{stm})}$ (12)

Quench: $\dfrac{\_\_\_ \; x \; \_\_\_}{R_{qc} \; x \; n_o(C)} =$ $\dfrac{\text{Mol}}{n_1(\text{quench})}$ (13)
(3)*

Oxygen: $\dfrac{\_\_\_ \; x \; \_\_\_}{R_{oc} \; x \; n_o(C)} =$ $\dfrac{\text{Mol}}{n_1(O_2\text{blst})}$ (14)
(1)*

Nitrogen: $\dfrac{[(\_\_\_ - \_\_\_) : \_\_\_] \; x \; \_\_\_}{[(R_{bc} - R_{oc}) : R_{oc}] \; x \; n_1(O_2\text{blst})} =$ $\dfrac{\text{Mol}}{n_1(N_2\text{blst})}$ (15)
(4)* (1)*

Reactor Gases

Carbon monoxide: $\dfrac{\_\_\_ \; x \; \_\_\_}{\alpha \; x \; n_o(C)} =$ $\dfrac{\text{Mol}}{n_2(CO)}$ (25)

Carbon dioxide: $\dfrac{\_\_\_ \; x \; \_\_\_}{(1-\alpha) \; x \; n_o(C)} =$ $\dfrac{\text{Mol}}{n_2(CO_2)}$ (26)

Water decomposed: $\dfrac{(2 - \_\_\_) \; x \; \_\_\_ \; - \; 2x \; \_\_\_}{(2 - \alpha) \; x \; n_o(C) \; - \; 2xn_1 \; (O_2\text{blst})} =$ $\dfrac{\text{Mol}}{n_2(H_2O_d)}$ (27)
(14)

Hydrogen: $\dfrac{\_\_\_ \; - \; \_\_\_ \; + \; \_\_\_}{n_o(H_2,\text{fc}) \; - \; n_o(S) \; + \; n(H_2O_d)} =$ $\dfrac{\text{Mol}}{n_2(H_2)}$ (28)
(27)

Nitrogen: $\dfrac{\_\_\_ \; + \; \_\_\_}{n_o(N_2) \; + \; n_1(N_2\text{blst})} =$ $\dfrac{\text{Mol}}{n_2(N_2)}$ (29)

Sulfur as hydrogen sulfide: $\dfrac{\_\_\_}{n_o(S)} =$ $\dfrac{\text{Mol}}{n_2(S)}$ (30)

Water Vapor: $\dfrac{\_\_\_ \; + \; \_\_\_ \; + \; \_\_\_ \; + \; 2x \; \_\_\_ \; - \; \_\_\_}{n_o(H_2O) \; + \; n_1(\text{stm}) \; + \; n_1(\text{qnch}) \; + \; 2xn_o(O_2) \; - \; n_2(H_2O_d)}$
(5) (27)

$\dfrac{\text{Mol}}{n_2(H_2O)}$ (31)

*See Table 2-1.

Basis: 100 lb coal, with moisture

Combustibles:

$$\frac{2\times \quad - 2\times \quad + \quad - \quad}{2n_o(C) - 2n_1(O_2 blst) + n_o(H_2, fc) - n_o(S)} =$$

(14)

$$\frac{\text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$

Total hot raw gas:

$$\frac{\quad + \quad + \quad + \quad + \quad}{n_o(C) + n_2(H_2,N,fg) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)}$$

(41) (42)

$$\frac{\text{Mol}}{\Sigma n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H_2S:

$$\frac{\quad \times 122{,}157}{n_o(H_2,CO) \times \Delta H_c(H_2,CO)} = \frac{\text{Btu}}{Q_c\ (\text{Sweet Gas})} \quad (34)$$

(32)

Heat release in reactor:

$$\frac{\quad \times 173{,}934 - [\quad - \quad] \times [2 \times 122{,}157]}{n_o(C) \times \Delta H_c(C) - [n_o(C) - n_1(O_2)] \times [2\Delta H_c(H_2,CO)]} = \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

(14) (32)

Heat release in combustion of H_2S:

$$\frac{\quad \times 241{,}092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{\quad + \quad + \quad}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \frac{\text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173{,}934 \times \quad \times [(1- \quad)/ \quad]}{\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]} \qquad \frac{\quad}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$n_o(H_2, fc) - n_o(S) =$ __________ $n_2(H_2, n, fg)$ (41)

$n_2(H_2O) + n_2(H_2O_d) =$ __________ $n_{1,2}(H_2O)$ (42)

(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{\_\_\_ \times 18 \times \_\_\_}{\underset{(12)}{n_1(stm)} \times 18 \times \underset{(5a)^*}{h(stm)}} \qquad \frac{\_\_\_\ Btu}{Q_1\ (stm)} \qquad (50)$$

Heat addition to reactor as blast gas (N_2,O_2), Btu:

$$\frac{[\_\_\_ + \_\_\_] \times 7.1(\_\_\_ -70°F) =}{\underset{(14)}{[n_1(O_2) + n_1(N_2)]} \times \underset{(6)^*}{C_p}(T_{in} -70°F)} \qquad \frac{\_\_\_\ Btu}{Q_1(N_2,O_2)} \qquad (51)$$

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - \_\_\_) \times 0.25 \times \_\_\_ =}{(100\ lb - \underset{**}{W_{evap}}) \times C'_p \times (T_{coal} - 70)} \qquad \frac{\_\_\_\ Btu}{Q_o(coal)} \qquad (52)$$

Heat loss from reactor as hot slag:

$$\frac{\_\_\_ \times 0.25 \times (\_\_\_ - 70) =}{\underset{(9)}{W(slag)} \times C'_p \times (T_{slag} - 70)} \qquad \frac{\_\_\_\ Btu}{Q(slag)} \qquad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{\_\_\_ \times \_\_\_ \times (\_\_\_ - \_\_\_) =}{\underset{(33)}{(\Sigma n_i)} \times \underset{(8)^*}{C_p(CFG)} \times (350 - 70)} \qquad \frac{\_\_\_\ Btu}{Q(CFG)} \qquad (54)$$

Total heat release to hot raw product gas:

$$\frac{\_\_\_ + \_\_\_ + \_\_\_ + \_\_\_ - \_\_\_}{Q(rctr) + Q_1(stm) + Q(N_2,O_2) + Q(coal) - Q(char)} \qquad \frac{=\ \_\_\_\ Btu}{Q(HFG)} \qquad (55)$$

Temperature reached in reactor:

$$\frac{\_\_\_ / [\_\_\_ \times \_\_\_] + 70}{Q(HFG)/[\underset{(7)^*}{C_p(HFG)} \times \Sigma n_i] + 70} \qquad \frac{\_\_\_}{T(rctr)} \qquad (56)$$

Case 1: This temperature should be at least 2800°F
Cases 1,2, &3: See Item (10), Table 2-1.

*See Table 2-1.

**See Design Basis.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\left[\underset{\substack{Q(HFG)\\(55)}}{\underline{\qquad}} - \underset{\substack{Q(CFG)\\(54)}}{\underline{\qquad}} - \underset{Q_1(Stm)}{\underline{\qquad}}\right] : \underset{\substack{h(stm,\ hp)\\(5b),\ \text{Table 2-1}}}{\underline{\qquad\qquad}} = \underset{W_3(stm,\ hp)}{\underline{\qquad\qquad\ \text{lb}}} \quad (57)$$

Case 2 only:

$$\left[\underset{\substack{Q(HFG)\\(55)}}{\underline{\qquad}} - \underset{\substack{Q(CFG)\\(54)}}{\underline{\qquad}}\right] : \underset{\substack{h(stm,\ hp)\\(5b),\ \text{Table 2-1}}}{\underline{\qquad\qquad}} = \underset{W_3(stm,\ hp)}{\underline{\qquad\qquad\ \text{lb}}} \quad (58)$$

Case 3 only:

$$\left[\underset{Q(HFG)}{\underline{\qquad}} - \underset{Q(CFG)}{\underline{\qquad}} - \underset{Q_1(N_2,O_2)}{\underline{\qquad}}\right] : \underset{h(stm,\ hp)}{\underline{\qquad\qquad}} = \underset{W_3(stm,\ hp)}{\underline{\qquad\qquad}} \quad (59)$$

ENERGY MANAGEMENT
Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\frac{21{,}296 \times \underline{\qquad\qquad}}{21{,}296 \times \underset{(15a)^{*}}{} n_1(O_2)} = \underline{\qquad\qquad\qquad\qquad} \frac{\text{Btu}}{E_c(\text{AIR})} \quad (60)$$

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\frac{9{,}218 \times \underline{\qquad\qquad}}{\underset{(15b)^{*}}{9{,}218} \times \underset{(14)}{n_1(O_2)}} = \underline{\qquad\qquad\qquad\qquad} \frac{\text{Btu}}{E_c(\text{AIR})} \quad (61)$$

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\frac{2{,}676 \times [\underline{\qquad} - \underline{\qquad}]}{\underset{(15c)^{*}}{2{,}676} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}]} = \underline{\qquad\qquad\qquad\qquad} \frac{\text{Btu}}{E_c(\text{FG})} \quad (63)$$

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\frac{1{,}354 \times [\underline{\qquad} - \underline{\qquad}]}{\underset{(16)^{*}}{1{,}354} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}]} = \underline{\qquad\qquad\qquad\qquad} \frac{\text{Btu}}{E_x(\text{FG})} \quad (64)$$

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$\frac{(\underline{\qquad}) \times [327 + 149 \times \underline{\qquad}] - 322\,[\underline{\qquad} \times \underline{\qquad} + \underline{\qquad}]}{W(\text{stm,hp}) \times [327 + 149 \times \underset{(14)^{*}}{Rps}] - 332\,[W(\text{stm,hp}) \times Rps + W_1(\text{stm})]} =$$

$$\underline{\qquad\qquad\qquad\qquad} \frac{\text{Btu}}{E_x(\text{stm})} \quad (65)$$

Where $W_1(\text{stm}) = 18 \times \underset{(12)}{n_1(\text{stm})}$ lb entered only for Cases 2 and 3.

*See Table 2-1.

PLANT SCALE PERFORMANCE
COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [\qquad\qquad]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb: } [Q_c(H_2,CO) + Q_c(H_2S)]} = \frac{\text{lb/hr}}{W(\text{Coal})} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
Item Sub i	Lb	n_i Mols	N_i Mols	Mol/Fract.	Mol/wt.	Lb
	71_i	72_i	73_i	74_i	75_i	76_i
Feed						
(70) a Coal	●100		●	—	NA	●
Blast				—		
(12) b Stm					18.016	
(14) c O_2					32.000	
(15) d N_2					28.010	
e(SubΣ)	●		●	NA	NA	●
(13) f Quench	●		●	NA	18.016	●
g Total	●		●	NA	NA	●
Effluent						
* h Evapn	●		●	—	NA	●
Sour Gas				—		
(25) j CO					28.010	
(26) k CO_2					44.010	
(28) l H_2					2.016	
(29) m N_2					28.016	
(30) n (H_2S)					34.076	
o Dry FG				1.000		
(31) p H_2O				—	18.016	
(33) q (HFG)	●		●	—		●
(9) r Char	●		●	—	NA	●
s Total	●		●	—	NA	●

Note: 73i/72i = 76i/71i = W(Coal)/100
71i/72i = 76i/73i = 75i

*See Design Basis.

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source Item	Component Sub.		Btu 80_i	kWhr 81_i	Btu 82_i	kWhr 83_i
Compression						
(60)	a	Oxy plant				
(61)	b	Air blast				
(63)	c	Raw fuel gas				
(13)*	d	Misc.				
	e	Total	●	●	●	●
Recovery Expansion						
(64)	f	Fuel gas				
(65)	g	Steam				
	h	Total	●	●	●	●
Net Demand						
(e,h)	j	Electric pwr	●	●	●	●
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas				
(36)	l	H_2S				
(35)	m	Reactor				
(38)	n	Char				
	o	Total	●		●	
(11)	p	Coal	●		●	
Total Energy to Plant						
(j,p)	q		●		●	

Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$

$81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$

*See Table 2-1.

PLANT COSTS

Capital Costs — $1000

Oxygen/Air Plant: (85)

$$\frac{[(\quad + \quad)/(\quad + \quad)]^{0.6}}{[(N_c + N_d)\ /\ (N^\circ_c + N^\circ_d)]^{0.6}} \ \frac{\times \quad\quad}{\times \quad C^\circ_1} = \underline{\qquad\qquad}_{\,C_1}$$

(73_c) (73_d) (See Note)

Gasification Module:

$$\frac{[\quad / \quad] \times \quad}{[N_q\ /\ N^\circ_q] \times C^\circ_2} = \underline{\qquad\qquad}_{\,C_2} \qquad (86)$$

(73_q) (see note)

Compression/Expansion:

$$\frac{(\quad / \quad) \times \quad}{(N_o/N^\circ_o) \times C^\circ_3} = \underline{\qquad\qquad}_{\,C_3} \qquad (87)$$

(73_o) (see note)

Gas Treatment Module:

$$\frac{\{1 + \quad \times [\quad - \quad]\} \times \{1 - \quad \times \ln[\quad / \quad]\} \times}{\{1 + a \times [W_o(S) - W^\circ_o(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^\circ(SO_2)]\} \times C^o_4} =$$

(17a)* (7) (17b)* (See Design Basis)

$$\underline{\qquad\qquad}_{\,C_4} \qquad (88)$$

*See Table 2-1.

Note: Values for C°, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module: $1,000

$[\quad]^{.5} \times \underline{\qquad} =$ ______ (89)

$[W(Coal) / W^{\circ}(Coal)]^{.5} \times C_5^{\circ}$ — C_5

Utilities, Piping, Waste Disposal: constant (90)

______ C_6

Direct Field Cost: (91)

Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6 =$ ______ C_7

Total Capital Cost (92)

$\underline{\quad} \times (\underline{\qquad}) =$ ______

$C_7 \times (C_8/C_7)$ — C_8
(18)*

Operating Costs, Annual, Based on 90% Service Factor $1,000

Coal @ W(Coal) lb/hr: (96)

$(\underline{\quad} / 2{,}000) \times (7{,}889\ hr/yr) \times \underline{\qquad} =$ ______

(W(Coal)/ 2,000) x (7,889 hr/yr) x ($/ton) — 0(coal)

Electric power @ E_D kW: (97)

$\underline{\qquad\qquad} \; \underline{\qquad} =$ ______

$(E_D) \times (7{,}889\ hr/yr)$ ($/kWhr) — 0(pwr)
(83g)

Catalyst, Chemicals, from Nominal Case:
Equipment, Supplies, Utilities
Operating Personnel
Maintenance Materials and Labor (98)

From Report, Subtotal, 0°(Misc) = ______ $0_{(Misc)}$

*See Table 2-1.

Fuel Gas Production over 25 Years, based on hourly rates

$$[\qquad\qquad - \qquad\qquad \times 3{,}163 - \qquad\qquad] \times 0.197 \times 10^6 =$$

$$\underset{(82k)}{[Q_c(\text{Sweet Gas})} - \underset{(20)}{W_o(\text{evap}) \times 3{,}163} - \underset{(19)^*}{Q(\text{Claus})]} \times 0.197 \times 10^6$$

$$\underline{\qquad\qquad\qquad}\;(99)$$
$$\Sigma Q(PG)$$

*Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^o, are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars: One Time	Amount, Thousands of Dollars: Recurring	Discount Factor	Discounted Cost, Thousands of Dollars
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment			●			●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs				●		●
(9)	● Total Project Costs						●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, $/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, $ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr — 250×10^6

Emission Of SO_2:

Product from combustion of fuel gas,
lb $SO_2/10^6$ Btu HHV (coal), ______ $e(SO_2)$

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	______	$W(C)$
Hydrogen	______	$W(H_2)$
Oxygen	______	$W(O_2)$
Nitrogen	______	$W(N_2)$
Sulfur	______	$W(S)$
Moisture	______	$W(H_2O)$
Ash	______	$W(Ash)$
Total	100	

Ash Softening Temperature = ______ °F

Ash Melting Temperature = ______ °F

Note: $W(evap) = W(H_2O) - W_o(H_2O)$

REACTOR PERFORMANCE
Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction γ = ______ (1)

Ratio $CO/(CO + CO_2)$, expected value α = ______ (2)

Feedstock and resulting char

Carbon: $\dfrac{\quad x \quad /12}{W_o(C) \ x \ (\gamma)/12} =$ $\dfrac{\quad Mol}{n_o(C)}$ (3)

Hydrogen: $\dfrac{\quad /2 - \quad /16}{W_o(H_2)/2 - W_o(O_2)/16} =$ $\dfrac{\quad Mol}{n_o(H_2, fc)}$ (4)

Oxygen: $\dfrac{\quad /32}{W_o(O_2)/32} =$ $\dfrac{\quad Mol}{n_o(O_2)}$ (5)

Nitrogen: $\dfrac{\quad /28}{W_o(N_2)/28} =$ $\dfrac{\quad Mol}{n_o(N_2)}$ (6)

Sulfur: $\dfrac{\quad /32}{W_o(S)/32} =$ $\dfrac{\quad Mol}{n_o(S)}$ (7)

Moisture: $\dfrac{\quad /18}{W_o(H_2O)} =$ $\dfrac{\quad Mol}{n_o(H_2O)}$ (8)

Char: $\dfrac{\quad + (\quad)x \quad}{W_o(Ash) + (1-\gamma) x \ W_o(C)} =$ $\dfrac{\quad lb}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ, HHV' coal:

$$\frac{\quad x(173,934) + \quad x(122,976) + \quad x(184,640)}{n_o(C) \ x \ \Delta H_c(C) + n_o(H_2, fc) \ x \ \Delta H_c(H_2) + n_o(S) \ x \ \Delta H_c(S)} =$$

$\dfrac{\quad Btu}{HHV' \ (coal)}$ (10)

($\Delta H_c(S)$ = At. wt. x 5,770 Btu/lb)

Heat of combustion @ full conversion, HHV (coal)

$$\frac{\quad + \quad x \quad x \ 173,934}{HHV \ (coal) + [1-\gamma)/\gamma] \ x \ n_o(C) \ x \ \Delta H_c(C)} = \frac{\quad Btu}{HHV \ (coal)}$$ (11)

Basis: 100 lb coal, with moisture

Blast

Steam: $$\frac{\qquad \times \qquad - [\qquad + \qquad + \qquad]}{R_{wc} \times n_o(C) - [n_o(H_2O) + 2N_o(O_2) + n_1(\text{Quench})]} = \frac{\qquad \text{Mol}}{n_1(\text{stm})} \quad (12)$$
(2)* (13)

Quench: $$\frac{\qquad \times \qquad}{R_{qc} \times n_o(C)} = \frac{\qquad \text{Mol}}{n_1(\text{quench})} \quad (13)$$
(3)*

Oxygen: $$\frac{\qquad \times \qquad}{R_{oc} \times n_o(C)} = \frac{\qquad \text{Mol}}{n_1(O_2\text{blst})} \quad (14)$$
(1)*

Nitrogen: $$\frac{[(\qquad\qquad) \div \qquad] \times \qquad}{[(R_{bc} - R_{oc}) \div R_{oc}] \times n_1(O_2\text{blst})} = \frac{\qquad \text{Mol}}{n_1(N_2\text{blst})} \quad (15)$$
(4)* (1)*

Reactor Gases

Carbon monoxide: $$\frac{\qquad \times \qquad}{\alpha \times n_o(C)} = \frac{\qquad \text{Mol}}{n_2(CO)} \quad (25)$$

Carbon dioxide: $$\frac{\qquad \times \qquad}{(1-\alpha) \times n_o(C)} = \frac{\qquad \text{Mol}}{n_2(CO_2)} \quad (26)$$

Water decomposed: $$\frac{(2 - \qquad) \times \qquad - 2\times \qquad}{(2 - \alpha) \times n_o(C) - 2 \times n_1(O_2\text{blst})} = \frac{\qquad \text{Mol}}{n_2(H_2O_d)} \quad (27)$$
(14)

Hydrogen: $$\frac{\qquad - \qquad + \qquad}{n_o(H_2,\text{fc}) - n_o(S) + n(H_2O_d)} = \frac{\qquad \text{Mol}}{n_2(H_2)} \quad (28)$$
(27)

Nitrogen: $$\frac{\qquad + \qquad}{n_o(N_2) + n_1(N_2\text{blst})} = \frac{\qquad \text{Mol}}{n_2(N_2)} \quad (29)$$

Sulfur as hydrogen sulfide: $$\frac{\qquad}{n_o(S)} = \frac{\qquad \text{Mol}}{n_2(S)} \quad (30)$$

Water Vapor: $$\frac{\qquad + \qquad + \qquad + 2\times \qquad - \qquad}{n_o(H_2O) + n_1(\text{stm}) + n_1(\text{qnch}) + 2\times n_o(O_2) - n_2(H_2O_d)}$$
(5) (27)

$$\frac{\qquad \text{Mol}}{n_2(H_2O)} \quad (31)$$

*See Table 2-1.

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Basis: 100 lb coal, with moisture

Combustibles:

$$\frac{2x \quad - \; 2x \quad + \quad - \quad}{2n_o(C) - 2n_1(O_2 blst) + n_o(H_2, fc) - n_o(S)} = \underline{\qquad} \frac{\text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$

(14)

Total hot raw gas:

$$\frac{\quad + \quad + \quad + \quad + \quad}{n_o(C) + n_2(H_2, N, fg) + n_{1,2}(H_2O) + n_2(N_2) + n_2(H_2S)}$$

(41) (42)

$$\underline{\qquad} \frac{\text{Mol}}{\Sigma n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H_2S:

$$\frac{\quad \times 122{,}157}{n_o(H_2, CO) \times \Delta H_c\,(H_2, CO)} = \underline{\qquad} \frac{\text{Btu}}{Q_c\ (\text{Sweet Gas})} \quad (34)$$

(32)

Heat release in reactor:

$$\frac{\quad \times 173{,}934 - [\quad - \quad] \times [2 \times 122{,}157]}{n_o(C) \times \Delta H_c(C) - [n_o(C) - n_1(O_2)] \times [2\Delta H_c\ (H_2, CO)]} = \underline{\qquad} \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

(14) (32)

Heat release in combustion of H_2S:

$$\frac{\quad \times 241{,}092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \underline{\qquad} \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{\quad + \quad + \quad}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \underline{\qquad} \frac{\text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173{,}934 \times \quad \times [(1- \quad)/ \quad]}{\Delta H_c(C) \times n_o(C) \times [(1-\gamma)/\gamma]} \quad \underline{\qquad} \frac{}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$n_o(H_2, fc) - n_o(S) =$ __________ $n_2(H_2, n, fg)$ (41)

$n_2(H_2O) + n_2(H_2O_d) =$ __________ $n_{1,2}(H_2O)$ (42)

(27)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

$$\frac{\qquad \times 18 \times \qquad}{n_1(\text{stm}) \times 18 \times h(\text{stm})} \qquad \frac{\qquad \text{Btu}}{Q_1\ (\text{stm})} \qquad (50)$$

(12) (5a)*

Heat addition to reactor as blast gas (N_2,O_2), Btu:

$$\frac{[\qquad + \qquad] \times 7.1(\qquad -70°F) =}{[n_1(O_2) + n_1(N_2)] \times C_p(T_{in} -70°F)} \qquad \frac{\qquad \text{Btu}}{Q_o(\text{coal})} \qquad (51)$$

(14)

Heat addition to reactor as warm coal from drying process:

$$\frac{(100 - \qquad) \times 0.25 \times \qquad =}{(100\ \text{lb} - W_{evap}) \times C'_p \times (T_{coal} - 70)} \qquad \frac{\qquad \text{Btu}}{Q_o(\text{coal})} \qquad (52)$$

Heat loss from reactor as hot slag:

$$\frac{\qquad \times 0.25 \times (\qquad - 70) =}{W(\text{slag}) \times C'_p \times (T_{slag} - 70)} \qquad \frac{\qquad \text{Btu}}{Q(\text{slag})} \qquad (53)$$

Heat loss from reactor as exit cool fuel gas:

$$\frac{\qquad \times \qquad \times (\qquad - \qquad) =}{(\Sigma n_i) \times C_p(\text{CFG}) \times (350 - 70)} \qquad \frac{\qquad \text{Btu}}{Q(\text{CFG})} \qquad (54)$$

Total heat release to hot raw product gas:

$$\frac{\qquad + \qquad + \qquad + \qquad - \qquad}{Q(\text{rctr}) + Q_1(\text{stm}) + Q(N_2,O_2) + Q(\text{coal}) - Q(\text{char})} = \frac{\qquad \text{Btu}}{Q(\text{HFG})} \qquad (55)$$

Temperature reached in reactor:

$$\frac{\qquad / [\qquad \qquad] + 70}{Q(\text{HFG})/[C_p(\text{HFG}) \times \Sigma n_i] + 70} \qquad \frac{\qquad}{T(\text{rctr})} \qquad (56)$$

Case 1: This temperature should be at least 2800°F
Cases 1,2, &3: See Item (10), Table 2-1.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

[______ - ______ - ______] : ______ = ______ lb (57)

[Q(HFG) - Q(CFG) - Q_1(Stm)] : h(stm, hp) W_3(stm, hp)

(55) (54) (5b), Table 2-1

Case 2 only:

[______ - ______] : ______ = ______ lb (58)

[Q(HFG) - Q(CFG)] : h(stm, hp) W_3(stm, hp)

(55) (54) (5b), Table 2-1

Case 3 only:

[______ - ______ - ______] : ______ = ______ (59)

[Q(HFG) - Q(CFG) - $Q_1(N_2, O_2)$] : h(stm, hp) W_3(stm, hp)

ENERGY MANAGEMENT
Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

21,296 x ______ = ______ Btu (60)
21,296 x $n_1(O_2)$ ______ $E_c(AIR)$
(15a)*

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

9,218 x ______ = ______ Btu (61)
9,218 x $n_1(O_2)$ ______ $E_c(AIR)$
(15b)* (14)

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

2,676 x [______ - ______] = ______ Btu (63)
2,676 x $[\Sigma n_i - n_2(H_2O)]$ ______ $E_c(FG)$
(15c)* (33) (31)

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

1,354 x [______ - ______] = ______ Btu (64)
1,354 x $[\Sigma n_i - n_2(H_2O)]$ ______ $E_x(FG)$
(16)* (33) (31)

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

(______) x [327 + 149 x ______] - 322 [______ x ______ + ______] =
W(stm,hp) x [327 + 149 x Rps] - 332 [W(stm,hp) x Rps + W_1(stm)]
(14)*

______ Btu (65)
E_x(stm)

Where W_1(stm) = 18 x n_1(stm) lb entered only for Cases 2 and 3.
(12)

*See Table 2-1.

PLANT SCALE PERFORMANCE
COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [\qquad\qquad]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb}: [Q_c(H_2,CO) + Q_c(H_2S)]} = \frac{\text{lb/hr}}{W(\text{Coal})} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
Item Sub i	Lb	n_i Mols	N_i Mols	Mol/Fract.	Mol/wt.	Lb-
	71_i	72_i	73_i	74_i	75_i	76_i
Feed						
(70) a Coal	•100		•	—	NA	•
Blast				—		
(13) b Stm					18.106	
(14) c O_2					32.000	
(15) d N_2					28.010	
e(SubΣ)	•		•	NA	NA	•
(12) f Quench	•		•	NA	18.016	•
g Total	•		•	NA	NA	•
Effluent						
(43) h Evapn	•		•	—	NA	•
Sour Gas				—		
(25) j CO					28.010	
(26) k CO_2					44.010	
(28) l H_2					2.016	
(29) m N_2					28.016	
(30) n (H_2S)					34.076	
o Dry FG				1.000		
(31) p H_2O	·			—	18.106	
(33) q (HFG)	•		•	—		•
(9) r Char	•		•	—	NA	•
s Total	•		•	—	NA	•

Note: $73i/72i = 76i/71i = W(\text{Coal})/100$
$71i/72i = 76i/73i = 75i$

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source Item	Component Sub.		Btu 80_i	kWhr 81_i	Btu 82_i	kWhr 83_i
Compression						
(60)	a	Oxy plant				
(61)	b	Air blast				
(63)	c	Raw fuel gas				
(13)*	d	Misc.				
	e	Total	.		.	.
Recovery Expansion						
(64)	f	Fuel gas				
(65)	g	Steam				
	h	Total	.		.	
Net Demand						
(e,h)	j	Electric pwr	.		.	
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas				
(36)	l	H_2S				
(35)	m	Reactor				
(38)	n	Char				
	o	Total	.		.	
(11)	p	Coal				
Total Energy to Plant						
(j,p)	q		.		.	

Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$
$81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$

*See Table 2-1.

PLANT COSTS

Capital Costs $1000

Oxygen/Air Plant: (85)

$$\frac{[(\quad + \quad)/(\quad + \quad)]^{0.6}}{[(N_k + N_l)\ /\ (N_k^{\circ} + N_l^{\circ})]^{0.6}} \ \frac{\times}{\times} \ \frac{\qquad}{C_1^{\circ}} = \underline{\qquad\qquad}\ C_1$$

(73$_c$) (73$_d$) (See Note)

Gasification Module:

$$\frac{[\quad / \quad]}{[N_h\ /\ N_h^{\circ}]} \ \frac{\times}{\times} \ \frac{\qquad}{C_2^{\circ}} = \underline{\qquad\qquad}\ C_2$$ (86)

(73$_q$) (see note)

Compression/Expansion:

$$\frac{(\quad / \quad)}{(N_f/N_f^{\circ})} \ \frac{\times}{\times} \ \frac{\qquad}{C_3^{\circ}} = \underline{\qquad\qquad}\ C_3$$ (87)

(73$_o$) (see note)

Gas Treatment Module:

$$\frac{\{1 + \quad \times [\quad - \quad]\} \times \{1 - \quad \times \ln[\quad / \quad]\} \times}{\{1 + a \times [W_o(s) - W_o^{\circ}(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^{\circ}(SO_2)]\} \times C_4^{\circ}} =$$

(17a)* (7) (17b)* (See Design Basis)

$$\underline{\qquad\qquad}\ C_4$$ (88)

*See Table 2-1.

Note: Values for C°, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:		$1,000	
$\dfrac{[\quad\quad]^{.5} \times \underline{\quad\quad}}{[W(Coal)\ /\ W^{\circ}(Coal)]^{.5} \times C_5^{\circ}}$ =		$\underline{\quad\quad}$ C_5	(89)
Utilities, Piping, Waste Disposal: constant		$\underline{\quad\quad}$ C_6	(90)
Direct Field Cost:			(91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6$ =		$\underline{\quad\quad}$ C_7	
Total Capital Cost			(92)
$\dfrac{\quad \times (\quad\quad)}{C_7 \times (C_8/C_7)}$ = (18)*		$\underline{\quad\quad}$ C_8	
Operating Costs, Annual, Based on 90% Service Factor		$1,000	
Coal @ W(Coal) lb/hr:			(96)
$\dfrac{(\quad / 2{,}000) \times (7{,}889\ hr/yr)}{(W(Coal)/ 2{,}000) \times (7{,}889\ hr/yr)} \times \dfrac{\quad}{(\$/ton)}$ =		$\underline{\quad\quad}$ 0(coal)	
Electric power @ E_D kW:			(97)
$\dfrac{\quad\quad}{(E_D\ ) \times (7{,}889\ hr/yr)}\ \dfrac{\quad}{(\$/kWhr)}$ = (83g)		$\underline{\quad\quad}$ 0(pwr)	
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor			(98)
From Report, Subtotal, 0°(Misc) =		$\underline{\quad\quad}$ $0_{(Misc)}$	

*See Table 2-1.

Fuel Gas Production over 25 Years, based on hourly rates

$$\frac{[\qquad\qquad - \qquad\qquad \times 3{,}163 - \qquad\qquad] \times 0.197 \times 10^6}{[Q_c(\text{Sweet Gas}) - W_o(\text{evap}) \times 3{,}163 - Q(\text{Claus})] \times 0.197 \times 10^6} =$$

(82k) (20) (19)*

______________ (99)
$\Sigma Q(PG)$

Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^o, are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars		Discount Factor	Discounted Cost, Thousands of Dollars
				One Time	Recurring		
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment						●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs						● ●
(9)	● Total Project Costs						●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, $/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, $ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

WORKSHEET FOR PLANT ANALYSIS

DESIGN BASIS

Reactor Capacity:

Heating value of reactor output, sour, Btu/hr — 250×10^6

Emission Of SO_2:

Product from combustion of fuel gas,
lb $SO_2/10^6$ Btu HHV (coal), ______ $e(SO_2)$

Ultimate Analysis Of Coal:

	% or lb per 100 lb coal	
Carbon	______	$W(C)$
Hydrogen	______	$W(H_2)$
Oxygen	______	$W(O_2)$
Nitrogen	______	$W(N_2)$
Sulfur	______	$W(S)$
Moisture	______	$W(H_2O)$
Ash	______	$W(Ash)$
Total	100	

Ash Softening Temperature = ______ °F

Ash Melting Temperature = ______ °F

Note: $W(evap) = W(H_2O) - W_o(H_2O)$

REACTOR PERFORMANCE

Basis: 100 lb coal, with moisture

Carbon gasification See Table 2-1, items (11) and (12).

Carbon conversion, expected fraction $\gamma =$ ______ (1)

Ratio $CO/(CO + CO_2)$, expected value $\alpha =$ ______ (2)

Feedstock and resulting char

Carbon: $\dfrac{\_\_\_\ \text{x}\ \_\_\_ /12}{W_o(C)\ \text{x}\ (\gamma)/12} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(C)}$ (3)

Hydrogen: $\dfrac{\_\_\_ /2 - \_\_\_ /16}{W_o(H_2)/2 - W_o(O_2)/16} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(H_2, fc)}$ (4)

Oxygen: $\dfrac{\_\_\_ /32}{W_o(O_2)/32} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(O_2)}$ (5)

Nitrogen: $\dfrac{\_\_\_ /28}{W_o(N_2)/28} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(N_2)}$ (6)

Sulfur: $\dfrac{\_\_\_ /32}{W_o(S)/32} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(S)}$ (7)

Moisture: $\dfrac{\_\_\_ /18}{W_o(H_2O)} =$ $\dfrac{\_\_\_\_\_\_\ \text{Mol}}{n_o(H_2O)}$ (8)

Char: $\dfrac{\_\_\_ + (\_\_\_)\text{x}\ \_\_\_}{W_o(Ash) + (1-\gamma)\text{x}\ W_o(C)} =$ $\dfrac{\_\_\_\_\_\_\ \text{lb}}{W_o(char)}$ (9)

Heat of combustion @ carbon conversion γ, HHV' coal:

$$\frac{\_\_\_\ \text{x}(173{,}934) + \_\_\_\ \text{x}(122{,}976) + \_\_\_\ \text{x}(184{,}640)}{n_o(C)\ \text{x}\ \Delta H_c(C) + n_o(H_2, fc)\ \text{x}\ \Delta H_c(H_2) + n_o(S)\ \text{x}\ \Delta H_c(S)} =$$

$\dfrac{\_\_\_\_\_\_\ \text{Btu}}{\text{HHV' (coal)}}$ (10)

($\Delta H_c(S)$ = At. wt. x 5,770 Btu/lb)

Heat of combustion @ full conversion, HHV (coal)

$\dfrac{\_\_\_ + \_\_\_\ \text{x}\ \_\_\_\ \text{x}\ 173{,}934}{\text{HHV (coal)} + [1-\gamma)/\gamma]\ \text{x}\ n_o(C)\ \text{x}\ \Delta H_c(C)} =$ $\dfrac{\_\_\_\_\_\_\ \text{Btu}}{\text{HHV (coal)}}$ (11)

Basis: 100 lb coal, with moisture

Blast

Steam: $\dfrac{\quad x \quad - [\quad + \quad + \quad]}{R_{wc} \times n_o(C) - [n_o(H_2O) + 2N_o(O_2) + n_1 \text{ (Quench)}]}$ =
(2)* (13)

$\dfrac{\text{Mol}}{n_1(\text{stm})}$ (12)

Quench: $\dfrac{x}{R_{qc} \times n_o(C)}$ = $\dfrac{\text{Mol}}{n_1(\text{quench})}$ (13)
(3)*

Oxygen: $\dfrac{x}{R_{oc} \times n_o(C)}$ = $\dfrac{\text{Mol}}{n_1(O_2\text{blst})}$ (14)
(1)*

Nitrogen: $\dfrac{[(\quad\quad) \div \quad] \; x}{[(R_{bc} - R_{oc}) \div R_{oc}] \times n_1(O_2\text{blst})}$ = $\dfrac{\text{Mol}}{n_1(N_2\text{blst})}$ (15)
(4)* (1)*

Reactor Gases

Carbon monoxide: $\dfrac{x}{\alpha \times n_o(C)}$ = $\dfrac{\text{Mol}}{n_2(CO)}$ (25)

Carbon dioxide: $\dfrac{x}{(1-\alpha) \times n_o(C)}$ = $\dfrac{\text{Mol}}{n_2(CO_2)}$ (26)

Water decomposed: $\dfrac{(2 - \quad)x \quad - 2x}{(2 - \alpha) \times n_o(C) - 2xn_1 \; (O_2\text{blst})}$ = $\dfrac{\text{Mol}}{n_2(H_2O_d)}$ (27)
(14)

Hydrogen: $\dfrac{\quad - \quad + \quad}{n_o(H_2,fc) - n_o(S) + n(H_2O_d)}$ = $\dfrac{\text{Mol}}{n_2(H_2)}$ (28)
(27)

Nitrogen: $\dfrac{\quad}{n_o(N_2) + n_1(N_2\text{blst})}$ = $\dfrac{\text{Mol}}{n_2(N_2)}$ (29)

Sulfur as hydrogen sulfide: $\dfrac{\quad}{n_o(S)}$ = $\dfrac{\text{Mol}}{n_2(S)}$ (30)

Water Vapor: $\dfrac{\quad + \quad + \quad + 2x \quad - \quad}{n_o(H_2O) + n_1(\text{stm}) + n_1(\text{qnch}) + 2xn_o(O_2) - n_2(H_2O_d)}$
(5) (27)

$\dfrac{\text{Mol}}{n_2(H_2O)}$ (31)

Basis: 100 lb coal, with moisture

Combustibles:

$$\frac{2x \quad - \; 2x \qquad + \qquad - \qquad}{2n_o(C) - \underset{(14)}{2n_1(O_2blst)} + n_o(H_2,fc) - n_o(S)} = \frac{\text{Mol}}{N_2(\text{cmbsl})} \quad (32)$$

Total hot raw gas:

$$\frac{\quad + \qquad + \qquad + \qquad + \quad}{n_o(C) + \underset{(41)}{n_2(H_2,N,fg)} + \underset{(42)}{n_{1,2}(H_2O)} + n_2(N_2) + n_2(H_2S)} \qquad \frac{\text{Mol}}{\Sigma n_i} \quad (33)$$

Heat Effects

Heating value of fuel gas, excepting H_2S:

$$\frac{\qquad x\ 122,157}{\underset{(32)}{n_o(H_2,CO)} \times \Delta H_c\ (H_2,CO)} = \frac{\text{Btu}}{Q_c\ (\text{Sweet Gas})} \quad (34)$$

Heat release in reactor:

$$\frac{\quad x\ 173,934 - [\qquad - \qquad] \times [2 \times 122,157]}{n_o(C) \times \Delta H_c(C) - \underset{(14)}{[n_o(C)-n_1(O_2)]} \times \underset{(32)}{[2\Delta H_c\ (H_2,CO)]}} = \frac{\text{Btu}}{Q(\text{reactor})} \quad (35)$$

Heat release in combustion of H_2S:

$$\frac{\qquad x\ 241,092}{n_2(H_2S) \times \Delta H_c(H_2S)} = \frac{\text{Btu}}{Q_c(H_2S)} \quad (36)$$

Sum of heat release effects:

$$\frac{\qquad + \qquad + \qquad}{Q_c(\text{Sweet gas}) + Q(\text{reactor}) + Q_c(H_2S)} = \frac{\text{Btu}}{\Sigma Q} \quad (37)$$

Heating value of unconverted carbon in char:

$$\frac{173,934 \times \qquad x[(1- \quad)/ \quad]}{\Delta H_c(C) \quad \times n_o(C) \quad x[(1-\gamma)/\gamma]} \qquad \frac{}{Q_c(\text{Char})} \quad (38)$$

Miscellaneous

$n_o(H_2,fc) - n_o(S) =$ ______ $n_2(H_2,n,fg)$ (41)

$n_2(H_2O) + \underset{(27)}{n_2(H_2O_d)} =$ ______ $n_{1,2}(H_2O)$ (42)

Basis: 100 lb coal, with moisture

Estimation of Steam Generation

Heat addition to reactor as steam blast (ref'd to 70°F), Btu:

_____ x 18 x _____ = _____ Btu (50)

n_1(stm) x 18 x h(stm) Q_1 (stm)

(12)   (5a)*

Heat addition to reactor as blast gas (N_2,O_2), Btu:

[_____ + _____] x 7.1(_____ -70°F) = _____ Btu (51)

[n_1(O_2) + n_1(N_2)] x C_p(T_{in}-70°F) Q_o(coal)

(14)

Heat addition to reactor as warm coal from drying process:

(100 - _____) x 0.25 x _____ = _____ Btu (52)

(100 lb - W_{evap}) x C'_p x (T_{coal} - 70) Q_o(coal)

Heat loss from reactor as hot slag:

_____ x 0.25 x (_____ - 70) = _____ Btu (53)

W(slag) x C'_p x (T_{slag} - 70)   Q(slag)

Heat loss from reactor as exit cool fuel gas:

_____ x _____ x (_____ - _____) = _____ Btu (54)

(Σn_i) x C_p(CFG) x (350 - 70)   Q(CFG)

Total heat release to hot raw product gas:

_____ + _____ + _____ + _____ - _____ = _____ Btu (55)

Q(rctr) + Q_1(stm) + Q(N_2,O_2) + Q(coal) - Q(char)   Q(HFG)

Temperature reached in reactor:

_____ /[_____] + 70   _____ (56)

Q(HFG)/[C_p(HFG) x Σn_i] + 70   T(rctr)

Case 1: This temperature should be at least 2800°F
Cases 1,2, &3: See Item (10), Table 2-1.

Basis: 100 lb coal, with moisture

Generation of high pressure steam by waste heat recovery:

Case 1 only:

$$\frac{[\_\_\_\_ - \_\_\_\_ - \_\_\_\_]}{[Q(HFG) - Q(CFG) - Q_1(Stm)]} \div \frac{\_\_\_\_}{h(stm, hp)} = \frac{\_\_\_\_ \text{ lb}}{W_3(stm, hp)} \quad (57)$$

(55) (54) (5b), Table 2-1

Case 2 only:

$$\frac{[\_\_\_\_ - \_\_\_\_]}{[Q(HFG) - Q(CFG)]} \div \frac{\_\_\_\_}{h(stm, hp)} = \frac{\_\_\_\_ \text{ lb}}{W_3(stm, hp)} \quad (58)$$

(55) (54) (5b), Table 2-1

Case 3 only:

$$\frac{[\_\_\_\_ - \_\_\_\_ - \_\_\_\_]}{[Q(HFG) - Q(CFG) - Q_1(N_2,O_2)]} \div \frac{\_\_\_\_}{h(stm, hp)} = \frac{\_\_\_\_}{W_3(stm, hp)} \quad (59)$$

ENERGY MANAGEMENT
Basis: 100 lb coal, with moisture

Compression Energy

Oxygen Plant Compressor (Oxygen Blast System Only):

Air is raised from 14.7 to 165 psia @ 70°F, and liquified.

$$\underset{(15a)^*}{21,296 \times n_1(O_2)} = \text{\_\_\_\_\_\_ Btu} \quad E_c(AIR) \qquad (60)$$

Air Blast Compressor (Air Blast System Only):

Air feed is raised from 14.7 to 50 psia @ 70°F:

$$\underset{(15b)^*}{9,218} \times \underset{(14)}{n_1(O_2)} = \text{\_\_\_\_\_\_ Btu} \quad E_c(AIR) \qquad (61)$$

Raw Gas Compression, dry:

Raw Gas Compression from 35 to 165 psia @ 100°F:

$$\underset{(15c)^*}{2,676} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}] = \text{\_\_\_\_\_\_ Btu} \quad E_c(FG) \qquad (63)$$

Recovered Energy

Fuel Gas Expansion: 135 to 40 psia:

$$\underset{(16)^*}{1,354} \times [\underset{(33)}{\Sigma n_i} - \underset{(31)}{n_2(H_2O)}] = \text{\_\_\_\_\_\_ Btu} \quad E_x(FG) \qquad (64)$$

Steam Expansion: 1,055 to 2.89, 165, 422 psia:

$$W(stm,hp) \times [327 + 149 \times \underset{(14)^*}{Rps}] - 332\, [W(stm,hp) \times Rps + W_1(stm)] =$$

$$\text{\_\_\_\_\_\_ Btu} \quad E_x(stm) \qquad (65)$$

Where $W_1(stm) = 18 \times \underset{(12)}{n_1(stm)}$ lb entered only for Cases 2 and 3.

*See Table 2-1.

PLANT SCALE PERFORMANCE
COAL HANDLING AND GASIFICATION

Basis: 100 lb coal or 1.0 hour, as noted

Coal Rate, lb/hr

$$\frac{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb} \div [\qquad\qquad]}{(250 \times 10^6 \text{ Btu/hr}) \times 100 \text{ lb} \div [Q_c(H_2,CO) + Q_c(H_2S)]} = \frac{\text{lb/hr}}{W(\text{Coal})} \quad (70)$$

Assemble previous results in 71_i or 72_i; compute entries for 73_i, 74_i, 76_i (See note).

Source Component	Basis: 100 lb Coal		Basis: 1 Hour's Operation			
Item Sub i	Lb	n_i Mols	N_i Mols	Mol/Fract.	Mol/wt.	Lb
	71_i	72_i	73_i	74_i	75_i	76_i
Feed						
(70) a Coal	•100		•	—	NA	•
Blast				—		
(13) b Stm					18.106	
(14) c O_2					32.000	
(15) d N_2					28.010	
e (SubΣ)	•		•	NA	NA	•
(12) f Quench	•		•	NA	18.016	•
g Total	•		•	NA	NA	•
Effluent						
(43) h Evapn	•		•	—	NA	•
Sour Gas				—		
(25) j CO					28.010	
(26) k CO_2					44.010	
(28) l H_2					2.016	
(29) m N_2					28.016	
(30) n (H_2S)					34.076	
o Dry FG				1.000		
(31) p H_2O				—	18.106	
(33) q (HFG)	•		•	—		•
(9) r Char	•		•	—	NA	•
s Total	•		•	—	NA	•

Note: 73i/72i = 76i/71i = W(Coal)/100
71i/72i = 76i/73i = 75i

PLANT SCALE PERFORMANCE
ENERGY EFFECTS

Basis: 100 lb coal or 1.0 hour, as noted

Mechanical Energy			Basis: 100 lb Coal		Basis: 1 Hour's Operation	
Source Item	Component Sub.		Btu 80_i	kWhr 81_i	Btu 82_i	kWhr 83_i
Compression						
(60)	a	Oxy plant				
(61)	b	Air blast				
(63)	c	Raw fuel gas				
(13)*	d	Misc.				
	e	Total	.		.	
Recovery Expansion						
(64)	f	Fuel gas				
(65)	g	Steam				
	h	Total	.		.	
Net Demand						
(e,h)	j	Electric pwr	.		.	
Heat Release Effects: Progressive combustion of coal to final products.						
(34)	k	Sweet gas				
(36)	l	H_2S				
(35)	m	Reactor				
(38)	n	Char				
	o	Total	.		.	
(11)	p	Coal				
Total Energy to Plant						
(j,p)	q		.		.	

Note: $82_i/80_i = 83_i/81_i = W(\text{Coal})/100$

$81_i/80_i = 83_i/82_i = 0.29281 \times 10^{-3}$

*See Table 2-1.

PLANT COSTS

Capital Costs $1000

Oxygen/Air Plant: (85)

$$\frac{[(\quad + \quad)/(\quad + \quad)]^{0.6}}{[(N_k + N_1)\ /\ (N_k^{\circ} + N_1^{\circ})]^{0.6}} \;\frac{\times}{\times}\; \frac{\qquad}{C_1^{\circ}} = \frac{\qquad\qquad}{C_1}$$

(73$_c$) (73$_d$) (See Note)

Gasification Module:

$$\frac{[\quad / \quad]}{[N_h\ /\ N_h^{\circ}]} \;\frac{\times}{\times}\; \frac{\qquad}{C_2^{\circ}} = \frac{\qquad\qquad}{C_2} \qquad (86)$$

(73$_q$) (see note)

Compression/Expansion:

$$\frac{(\quad / \quad)\ \times \qquad}{(N_f/N_f^{\circ})\ \times\ C_3^{\circ}} = \frac{\qquad\qquad}{C_3} \qquad (87)$$

(73$_o$) (see note)

Gas Treatment Module:

$$\frac{\{1 + \quad \times [\quad - \quad]\} \times \{1 - \quad \times \ln[\quad / \quad]\} \times \qquad}{\{1 + a \times [W_o(s) - W_o^{\circ}(S)]\} \times \{1 - b \times \ln[e(SO_2)/e^{\circ}(SO_2)]\} \times C_4^{\circ}} =$$

(17a)* (7) (17b)* (See Design Basis)

$$\frac{\qquad\qquad}{C_4} \qquad (88)$$

*See Table 2-1.

Note: Values for C°, for the nominal cases, are in the Final Report, Appendix F.

Coal Preparation Module:		$1,000	
$\frac{[\qquad]^{.5} \times \qquad}{[W(\text{Coal}) \,/\, W^{\circ}(\text{Coal})]^{.5} \times C_5^{\circ}}$	=	C_5	(89)
Utilities, Piping, Waste Disposal: constant		C_6	(90)
Direct Field Cost:			(91)
Sum: $C_1 + C_2 + C_3 + C_4 + C_5 + C_6$ =		C_7	
Total Capital Cost			(92)
$\frac{\quad \times (\qquad)}{C_7 \times (C_8/C_7)}$ (18)*	=	C_8	
Operating Costs, Annual, Based on 90% Service Factor		$1,000	
Coal @ W(Coal) lb/hr:			(96)
$\frac{(\quad / 2{,}000) \times (7{,}889 \text{ hr/yr})}{(W(\text{Coal})/ 2{,}000) \times (7{,}889 \text{ hr/yr})} \times \frac{\qquad}{(\$/\text{ton})}$	=	0(coal)	
Electric power @ E_D kW:			(97)
$\frac{\qquad}{(E_D\ ) \times (7{,}889 \text{ hr/yr})} \; \frac{\qquad}{(\$/\text{kWhr})}$ (83g)	=	0(pwr)	
Catalyst, Chemicals, from Nominal Case: Equipment, Supplies, Utilities Operating Personnel Maintenance Materials and Labor			(98)
From Report, Subtotal, 0°(Misc) =		0(Misc)	

*See Table 2-1.

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Fuel Gas Production over 25 Years, based on hourly rates

$$\frac{[\quad\quad - \quad\quad \times 3{,}163 - \quad\quad] \times 0.197 \times 10^6}{[Q_c(\text{Sweet Gas}) - W_o(\text{evap}) \times 3{,}163 - Q(\text{Claus})] \times 0.197 \times 10^6} =$$

(82k) (20) (19)*

______ (99)

$\Sigma Q(PG)$

Next use the Discounted Costs of Gas Production form provided for summing discounted future costs.

Note 1: Capital costs of the nominal plant, C^o, are in the Final Report.

*See Table 2-1.

DISCOUNTED COSTS OF GAS PRODUCTION

Line Number	Cost Element	Differential Inflation Rate	Project Year	Amount, Thousands of Dollars: One Time	Amount, Thousands of Dollars: Recurring	Discount Factor	Discounted Cost, Thousands of Dollars
(1)	First-Year Construction	+0	2		17%	0.867	
(2)	Second-Year Construction	+0	3		34%	0.788	
(3)	Third-Year Construction	+0	4		49%	0.717	
(4)	● Total Investment						●
(5)	Coal	+5	5-29			12.268	
(6)	Electricity	+6	5-29			14.057	
(7)	Operating Labor and Materials	+0	5-29			6.505	
(8)	● Total Operating Costs						● ●
(9)	● Total Project Costs						●
(10)	Fuel Oil Alternative	+8	5-29			18.631	
(11)	Energy Available over 25 years, billions of Btu						
(12)	Product Gas Unit Cost, $/million Btu (line 9 divided by line 11)						
(13)	Fuel Oil Alternative Unit Cost, $ million Btu (line 10 divided by line 11)						
(14)	Savings/Investment Ratio, SIR = (line 10 - line 8)/line 4						

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ESTIMATING PROCEDURE WORK SHEET FOR EFFECTS OF FUEL CHANGES ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS										
1	BOILER TYPE, WT-WATER TUBE / FT-FIRE TUBE											
2	STEAM TEMPERATURE	F										
	INITIAL CONDITIONS											
3	FUEL											
4	EXCESS AIR	%										
5	FRACTION OF HEAT TRANSFERRED BY RADIATION											
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION											
7	CHECK, 5 + 6 = 1.00											
8	COMBUSTION TEMPERATURE, F(3 AND 4)	F										
9	COMBUSTION TEMPERATURE 8 + 460.	R										
10	TEMPERATURE FUNCTION, F 9											
11	EMISSIVITY, F(3 AND 8)											
12	COMBUSTION PRODUCTS RATE, F(3 AND 4)	$\frac{lb}{10,000\ BTU}$										
	NEW FUEL CONDITIONS											
13	FUEL GAS HIGH HEATING VALUE	$\frac{BTU}{CU.FT.}$										
14	EXCESS AIR	%										
15	COMBUSTION TEMPERATURE, F(13 AND 14)	F										
16	COMBUSTION TEMPERATURE, 15 + 460.	R										
17	TEMPERATURE FUNCTION, F 16											
18	EMISSIVITY, F(13 AND 15)											
19	COMBUSTION PRODUCTS RATE, F(13 AND 14)	$\frac{lb}{10,000\ BTU}$										
20	RATIO OF PRODUCTS, 19 ÷ 12 $\leq$ 1.10											

STEP NO.	COMPUTATIONAL STEP	UNITS										
	EFFECTS ON RADIANT HEAT TRANSFER											
21	$\left(\frac{q_2}{q_1}\right)_r = \frac{18}{11} \times \frac{17}{10}$											
22	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{21}{20}$											
23	STACK TEMPERATURE,											
	WATER TUBE = 2 + 100.	F										
	FIRE TUBE = 2 + 200.	F										
24	$\Delta T_r =$ 5 × (8 − 23)	F										
25	$T_{tb1} =$ 8 − 24	F										
26	$T_{tb2} =$ 15 − 22 × 24	F										
	EFFECTS ON CONVECTIVE HEAT TRANSFER											
27	$\frac{T_{tb2} - T_s}{T_{tb1} - T_s} = \frac{26 - 2}{25 - 2}$											
28	$(U_e)_2/(U_e)_1$, F 20											
	$(U_j)_2/(U_j)_1$, FOR FIRE TUBE											
29	U_2, F 28											
30	U_2/U_1,											
	WATER TUBE = 29 — 0.5											
	FIRE TUBE = 28											
31	$\left(\frac{q_2}{q_1}\right)_c =$ 30 × 27											
32	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{31}{20}$											

STEP NO.	COMPUTATIONAL STEP	UNITS										
	TOTAL PERFORMANCE EFFECTS											
33	$\left(\frac{q_2}{q_1}\right)_{TOTAL} = (5 \times 21) + (6 \times 31)$											
34	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_{TOTAL} = (5 \times 22) + (6 \times 32)$											
35	$\Delta T_{comb\ 1} = 8 - 70.$	F										
36	$\Delta T_{comb\ 2} = 15 - 70.$	F										
37	$\left(\frac{EFF.\ 2}{EFF.\ 1}\right)_{TOTAL} = \frac{34 \times 35}{35}$											

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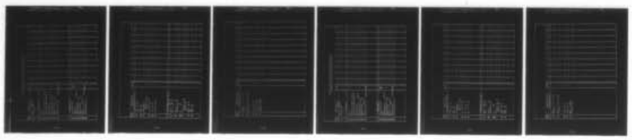

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ESTIMATING PROCEDURE WORK SHEET FOR EFFECTS OF FUEL CHANGES
ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS										
1	BOILER TYPE, WT-WATER TUBE FT-FIRE TUBE											
2	STEAM TEMPERATURE	F										
	INITIAL CONDITIONS											
3	FUEL											
4	EXCESS AIR	%										
5	FRACTION OF HEAT TRANSFERRED BY RADIATION											
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION											
7	CHECK, 5 + 6 = 1.00											
8	COMBUSTION TEMPERATURE, F(3 AND 4)	F										
9	COMBUSTION TEMPERATURE 8 + 460.	R										
10	TEMPERATURE FUNCTION, F 9											
11	EMISSIVITY, F(3 AND 8)											
12	COMBUSTION PRODUCTS RATE, F(3 AND 4)	$\frac{lb}{10,000\ BTU}$										
	NEW FUEL CONDITIONS											
13	FUEL GAS HIGH HEATING VALUE	$\frac{BTU}{CU.FT.}$										
14	EXCESS AIR	%										
15	COMBUSTION TEMPERATURE, F(13 AND 14)	F										
16	COMBUSTION TEMPERATURE, 15 + 460.	R										
17	TEMPERATURE FUNCTION, F 16											
18	EMISSIVITY, F(13 AND 15)											
19	COMBUSTION PRODUCTS RATE, F(13 AND 14)	$\frac{lb}{10,000\ BTU}$										
20	RATIO OF PRODUCTS, 19 ÷ 12 $\leq$ 1.10											

STEP NO.	COMPUTATIONAL STEP	UNITS										
	EFFECTS ON RADIANT HEAT TRANSFER											
(21)	$\left(\frac{q_2}{q_1}\right)_r = \frac{(18)}{(11)} \times \frac{(17)}{(10)}$											
(22)	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{(21)}{(20)}$											
(23)	STACK TEMPERATURE,											
	WATER TUBE = (2) + 100.	F										
	FIRE TUBE = (2) + 200.	F										
(24)	ΔT_r = (5) x ((8) − (23))	F										
(25)	T_{tb1} = (8) − (24)	F										
(26)	T_{tb2} = (15) − (22) x (24)	F										
	EFFECTS ON CONVECTIVE HEAT TRANSFER											
(27)	$\frac{T_{tb2} - T_s}{T_{tb1} - T_s} = \frac{(26) - (2)}{(25) - (2)}$											
(28)	$(U_e)_2/(U_e)_1$, F (20)											
	$(U_i)_2/(U_i)_1$, FOR FIRE TUBE											
(29)	U_2, F (28)											
(30)	U_2/U_1,											
	WATER TUBE = (29) — (0.5)											
	FIRE TUBE = (28)											
(31)	$\left(\frac{q_2}{q_1}\right)_c$ = (30) x (27)											
(32)	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{(31)}{(29)}$											

STEP NO.	COMPUTATIONAL STEP	UNITS										
	TOTAL PERFORMANCE EFFECTS											
33	$\left(\frac{q_2}{q_1}\right)_{TOTAL} = (5 \times 21) + (6 \times 31)$											
34	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_{TOTAL} = (5 \times 22) + (6 \times 32)$											
35	$\Delta T_{comb\ 1} = 8 - 70.$	F										
36	$\Delta T_{comb\ 2} = 15 - 70.$	F										
37	$\left(\frac{EFF.\ 2}{EFF.\ 1}\right)_{TOTAL} = \frac{34 \times 35}{35}$											

ESTIMATING PROCEDURE WORK SHEET FOR EFFECTS OF FUEL CHANGES ON INDUSTRIAL SATURATED STEAM BOILER PERFORMANCE

STEP NO.	COMPUTATIONAL STEP	UNITS										
1	BOILER TYPE, WT-WATER TUBE / FT-FIRE TUBE											
2	STEAM TEMPERATURE	F										
	INITIAL CONDITIONS											
3	FUEL											
4	EXCESS AIR	%										
5	FRACTION OF HEAT TRANSFERRED BY RADIATION											
6	FRACTION OF HEAT TRANSFERRED BY CONVECTION											
7	CHECK, 5 + 6 = 1.00											
8	COMBUSTION TEMPERATURE, F(3 AND 4)	F										
9	COMBUSTION TEMPERATURE 8 + 460.	R										
10	TEMPERATURE FUNCTION, F 9											
11	EMISSIVITY, F(3 AND 8)											
12	COMBUSTION PRODUCTS RATE, F(3 AND 4)	lb / 10,000 BTU										
	NEW FUEL CONDITIONS											
13	FUEL GAS HIGH HEATING VALUE	BTU / CU.FT.										
14	EXCESS AIR	%										
15	COMBUSTION TEMPERATURE, F(13 AND 14)	F										
16	COMBUSTION TEMPERATURE, 15 + 460.	R										
17	TEMPERATURE FUNCTION, F 16											
18	EMISSIVITY, F(13 AND 15)											
19	COMBUSTION PRODUCTS RATE, F(13 AND 14)	lb / 10,000 BTU										
20	RATIO OF PRODUCTS, 19 ÷ 12 ≤ 1.10											

STEP NO.	COMPUTATIONAL STEP	UNITS											
	EFFECTS ON RADIANT HEAT TRANSFER												
(21)	$\left(\frac{q_2}{q_1}\right)_r = \frac{(18)}{(11)} \times \frac{(17)}{(10)}$												
(22)	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_r = \frac{(21)}{(20)}$												
(23)	STACK TEMPERATURE,												
	WATER TUBE = (2) + 100.	F											
	FIRE TUBE = (2) + 200.	F											
(24)	ΔT_r = (5) × ((8) − (23))	F											
(25)	T_{th1} = (8) − (24)	F											
(26)	T_{th2} = (15) − (22) × (24)	F											
	EFFECTS ON CONVECTIVE HEAT TRANSFER												
(27)	$\frac{T_{th2} - T_s}{T_{th1} - T_s} = \frac{(26) - (2)}{(25) - (2)}$												
(28)	$(U_o)_2 / (U_o)_1$, F (20)												
	$(U_i)_2 / (U_i)_1$, FOR FIRE TUBE												
(29)	U_2, F (28)												
(30)	U_2 / U_1,												
	WATER TUBE = (29) − (0.5)												
	FIRE TUBE = (29)												
(31)	$\left(\frac{q_2}{q_1}\right)_c$ = (30) × (27)												
(32)	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_c = \frac{(31)}{(28)}$												

STEP NO.	COMPUTATIONAL STEP	UNITS										
	TOTAL PERFORMANCE EFFECTS											
33	$\left(\frac{q_2}{q_1}\right)_{TOTAL} = (5 \times 21) + (6 \times 31)$											
34	$\left(\frac{\Delta T_2}{\Delta T_1}\right)_{TOTAL} = (5 \times 22) + (6 \times 32)$											
35	$\Delta T_{comb\,1} = 8 - 70.$	F										
36	$\Delta T_{comb\,2} = 15 - 70.$	F										
37	$\left(\frac{EFF.\,2}{EFF.\,1}\right)_{TOTAL} = \frac{34 \times 36}{35}$											